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Marine Ecosystems
Biodiversity, Ecosystem Services
and Human Impacts

Edited by Ana Marta Gonçalves



Marine Ecosystems -
Biodiversity, Ecosystem
Services and Human
Impacts

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Marine Ecosystems – Biodiversity, Ecosystem Services and Human Impacts

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Contributors

Abhijit Mallik, Suchismita Prust, Puja Chakraborty, Shyamal Chandra Sukla Das, Shashi Bhushan, Adib Ali Saad, Lana Ezaldin Khrema, Melekote Nagabhushan Arun, Rapolu Mahender Kumar, Banugu Sreedevi, Guntupalli Padmavathi, Pallakonda Revathi, Neha Pathak, Dayyala Srinivas, Raman Meenakshi Sundaram, Sailaja Nori, Rajuddin Syamsuddin, Ana Marta Gonçalves, Andreia Filipa Mesquita, Fernando José Mendes Gonçalves, Neila Annabi-Trabelsi, Mohammad Ali, Genuario Belmonte, Habib Ayadi, Wassim Guerhazi

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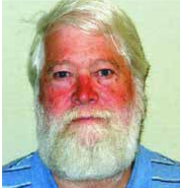
IntechOpen Book Series
Environmental Sciences
Volume 15

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editor



Dr. Ana Marta Gonçalves obtained a Ph.D. in Biology with a specialty in Ecology from the University of Coimbra, Portugal, in collaboration with Ghent University, Belgium, in 2011. Since 2019, she has been an auxiliary researcher at the Department of Life Sciences, Faculty of Sciences and Technology, University of Coimbra. During her research career, Dr. Gonçalves obtained several grants in highly international competitive calls, including the 2008 MARS award for young scientists funded by the Royal Netherlands Institute for Sea Research (NIOZ) and the Foundation for Science and Technology (FCT, Portugal) grants, and an honorable mention for the Impact of International Publications in 2022, according to Web of Science, by the Director of the Faculty of Sciences and Technology, University of Coimbra. She was a member of the board of directors of the research unit Marine and Environmental Sciences Centre (MARE). Currently, she is the chair of the *Society of Environmental Toxicology and Chemistry* (SETAC) Europe Education Committee, coordinator of LTsER Estuaries platform, eLTER coordinator of the Working Group Sites and Platform Forum (SPF) Training Group, member of the board of directors of IMAR – Institute of Sea, an associate member (representative) of the Euro-Marine and IMBRSea networks, and a coordinator of La Caixa Foundation fellowship programs. Since 2016, Dr. Gonçalves has been a member of the Scientific Council of Institute for Interdisciplinary Research, University of Coimbra. She is a journal editor and reviewer and has edited one book. Dr. Gonçalves is an advisory board member for Food Sciences and Technology and Toxicology. She is also a coordinator and research member of several national and international projects. She holds various administrative and science management positions in international networks. Dr. Gonçalves has supervised more than 140 graduate and post-graduate students and published more than 114 indexed papers and more than 55 book chapters. Dr. Gonçalves develops her work in the field of biological sciences, in the frontier of aquatic ecology and ecotoxicology, and biochemical pathways, assessing potential changes in trophic food webs, from primary producers to top predators, exposed to chemical stressors and climatic changes. She also researches marine biotechnology and the valorization of marine resources with industrial applications like food, biomedicine, pharmaceutical and agriculture novel products. Dr. Gonçalves dedicates part of her time to health and ocean literacy and environmental education. Her areas of specialization include marine biotechnology aquatic ecotoxicology, trophic food webs, global changes, anthropogenic impacts, microplastic pollution, biochemical analysis (fatty acid and carbohydrate profiles, proteins), biomarkers, bioindicators, aquatic ecology, estuarine plankton dynamics, long-term changes of plankton communities, aquaculture, and environmental education.

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Preface

Marine ecosystems are among the most populated habitats in the world. Their richness is given by an incredible number of marine organisms that provide human beings with ecosystem services. The Millennium Ecosystem Assessment defined “ecosystem services” as “the benefits that people obtain from ecosystems.” Marine biota is a great source of ecosystem services.

Ecosystem services are dependent on natural ecosystem functions, thus it is important to preserve our planet and its habitats. For example, the provision of seafood is the most exploited ecosystem service, which is a result of a combination of primary and secondary production, biogeochemical cycling, food web dynamics, and so on. The economic benefits are also encouraging; it has been estimated that marine ecosystem services are valued at \$50 trillion per year. Marine species mostly used for human benefits are principally known in the food industry, but they can also assure several benefits in different biotechnological applications, such as in the nutraceutical, pharmaceutical, or cosmetics industries, as demonstrated by studies on seaweeds and microalgae. The interest in and search for new natural compounds from marine biodiversity to discover novel bioactive substances has increased in the last decade. It is expected that many naturally bioactive marine compounds with novel structures and bioactivities may be found among marine metabolites. Still, with the constant and aggravated depletion of our natural environments, such as supplies of water and soils, the foundations of our food production are compromised. In this scenario, there is a great interest in marine organisms such as macroalgae biomass and resource exploration, with a substantial body of evidence supporting the nutritional potential of macroalgae. Marine macroalgae produce significant amounts of primary and secondary metabolites that present a wide variety of bioactive properties, including antioxidant, antiviral, antimicrobial, antitumoral, anti-inflammatory, anti-aging, or immunomodulatory potential, along with antibiotic properties. These molecules are promising candidates for many possible applications such as in pharmaceutical, nutraceutical, cosmetics, and medical industries as well as agriculture and feeding. These applications may benefit the human quality of life. Among benthonic organisms, mussels are also used in different sectors, for example, the anti-inflammatory agent contained in Lyprinol may be extracted from a green-lipped mussel originating from New Zealand. Moreover, sponges and coral are also rich in bioactive compounds that could be useful for future studies and the development of new human services. Indeed, ecosystem services offered by marine resources are diverse. For example, mangrove ecosystems are important to ensure nursery and breeding habitats for many important fish species that can be exploited for aquaculture, providing other important services associated with habitat functions and protection. Connected with the extraction and harvesting of natural marine resources are activities related to tourism and culture. Commercial fishing and marine tourism are both highly dependent on ecosystems, but marine tourism has been identified as having a lower impact on the environment and higher monetary value. Unfortunately, anthropogenic impact affects our ecosystems, leading to habitat degradation, pollution, overfishing, and more. Due to the unsustainable human exploitation of natural

resources, ecosystem services are limited. Thus, to avoid the complete depletion of marine environments and to have functional ecosystem services over time, it is necessary to preserve and adopt sustainable uses of the environment. The Marine Strategy Framework Directive suggests the use of biological indicators to recognize stressed ecosystems to facilitate the process of restoration. The importance of zooplankton groups and their contribution to ecosystem services is apparent by examining the ecological roles of zooplankton and their impact on fish recruitment and fishery management.

This edited volume is a collection of reviewed and relevant research chapters concerning the developments within marine ecosystems. Chapters in this book include:

Chapter 1: “Evaluation of the Water Quality and the Eutrophication Risk in Mediterranean Sea Area: A Case Study of the Gulf of Gabès”

Chapter 2: “Biostimulant Properties of Marine Bioactive Extracts in Plants: Incrimination toward Sustainable Crop Production in Rice”

Chapter 3: “Seaweed *Kappaphycus alvarezii* Cultivation for Seagrass Ecosystem Conservation”

Chapter 4: “Marine Bivalves’ Ecological Roles and Humans-Environmental Interactions to Achieve Sustainable Aquatic Ecosystems”

Chapter 5: “Non-Indigenous Marine Fish in Syria: Past, Present and Impact on Ecosystem, and Human Health”

Chapter 6: “Fish Otolith Microchemistry as a Biomarker of Metal Pollution in the Estuarine Ecosystem”

Ana Marta Gonçalves
Faculty of Science and Technology,
Department of Life Sciences,
University of Coimbra,
Coimbra, Portugal

Chapter 1

Evaluation of the Water Quality and the Eutrophication Risk in Mediterranean Sea Area: A Case Study of the Gulf of Gabès

Neila Annabi-Trabelsi, Mohammad Ali, Genuario Belmonte, Habib Ayadi and Wassim Guermazi

Abstract

The Gulf of Gabès, located in southern Tunisia, is a distinct and ecologically significant area in the Mediterranean Sea. Unfortunately, this dynamic marine ecosystem is experiencing cultural eutrophication, a process where water enrichment with nutrients like phosphorus and nitrogen salts leads to excessive algae growth, disrupting the ecological equilibrium and degrading water quality. In the Gulf of Gabès, key sources of nutrient pollution include industrial discharges, urbanization and agriculture. Eutrophication's effects here include harmful algal blooms, oxygen depletion, and declining water quality, upsetting the marine ecosystem's balance and impacting both fish and aquatic life. Nutrient enrichment interacts with trace metal pollution, overfishing and climate change. Future research must acknowledge and consider the complex interactions among these variables. Efforts in the Gulf of Gabès to address eutrophication involve tighter industrial regulations, enhanced agriculture and improved wastewater management, all crucial for preserving the marine environment's integrity and ensuring sustainability for the future.

Keywords: eutrophication, phosphorus, phytoplankton, zooplankton, algal blooms

1. Introduction

Cultural eutrophication poses a severe environmental and economic challenge in coastal marine ecosystems across the globe [1–3]. According to the European Union's definition, cultural eutrophication involves enriching water with nutrients, especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned [4]. This kind of pollution by nutrients is resulting from anthropogenic activities including industry, agriculture and sewage disposal [5]. The repercussions of cultural eutrophication extend to coastal ecosystem biodiversity and the services they give to society such as protection from coastal erosion and flooding, or fish production [6].

Eutrophication is mostly accompanied by hypoxia and an increase in the biomass of nuisance algal taxa [7]. In fact, eutrophication is an important factor contributing to the increased frequency and diversity of harmful algal blooms [8] and shifts in the zooplankton community [7]. Despite the fact the Mediterranean Sea is generally considered of good quality [9, 10] and classified as nutrient-poor and oligotrophic [11], eutrophication problems began emerging in the 1960s [12], mainly situated in areas of encircled gulfs and bays near big cities, in estuarine areas and near ports [13–17]. The Gulf of Gabès, situated on the southeastern coast of Tunisia, faces pollution from anthropogenic and industrial activities, and its coastal area showed signs of eutrophication [18]; continuous and increasing deterioration of the coastal waters of the Gulf was reported since the industrialization [19–21].

2. The Gulf of Gabès: main characteristics

Situated in southeastern Tunisia, the Gulf of Gabès, also known as “Petite Syrte”, stretches from 9.5 to 12°E in longitude and from 33 to 35.5°N in latitude. It extends from “Ras Kapoudia” in the north to the Tunisian–Libyan border in the south, encompassing a coastline exceeding 400 km (**Figure 1**). It shelters various islands (Kerkenneh, Kneiss and Jerba) and lagoons (Boughrara and El Bibane).

It is characterized by a semiarid Mediterranean climate, shallow waters, weak currents, high salinity and high temperature. The Gulf’s circulation is predominantly influenced by tides and anticyclonic winds [22].

The Gulf has the highest tidal range in the Mediterranean Sea (maximum >2 m), essentially due to the low slope of the continental shelf and the shallow depth, which maintains its horizontal dimensions close to the resonance phenomena [22, 23].

Since industrialization in 1970, the Gulf of Gabès has been heavily impacted by industrial wastes and described as one of the most human-impacted coastal areas in the Mediterranean Sea [21]. Diverse untreated pollutants from liquid and solid wastes discharged from industrial and domestic activities (crude phosphate treatment, chemical processing plants, tanneries and textile mills) have severely degraded the Gulf of Gabès [24, 25]. The phosphate fertilizer industry is mediated as the major source of pollution. The most important phosphate industry group (Tunisian Chemical Group: TCG) was set in Gabès city. Two other companies (SIAPE and GRANUPHOS) are located in Sfax city, and recently, another one (SIAPE II) has been launched in Skhira. The unregulated disposal of phosphogypsum (PG), a byproduct of the phosphate fertilizer industry, into the Gulf of Gabès at a daily rate ranging from 1000 to 13,000 tons, stands as the primary factor responsible for the deterioration of this ecosystem [26, 27].

3. Causes of eutrophication in the Gulf of Gabès

Phosphogypsum (PG) industrial effluents released into the Gulf of Gabès are notably acidic and carry elevated levels of fluoride and phosphate. Additionally, they contain variable concentrations of heavy metals such as cadmium, chromium, copper, zinc and lead, along with radionuclides [28, 29]. The study of El Kateb et al. [30] clearly established that the substantial discharge of PG is a leading cause of eutrophication in the Gulf of Gabès.

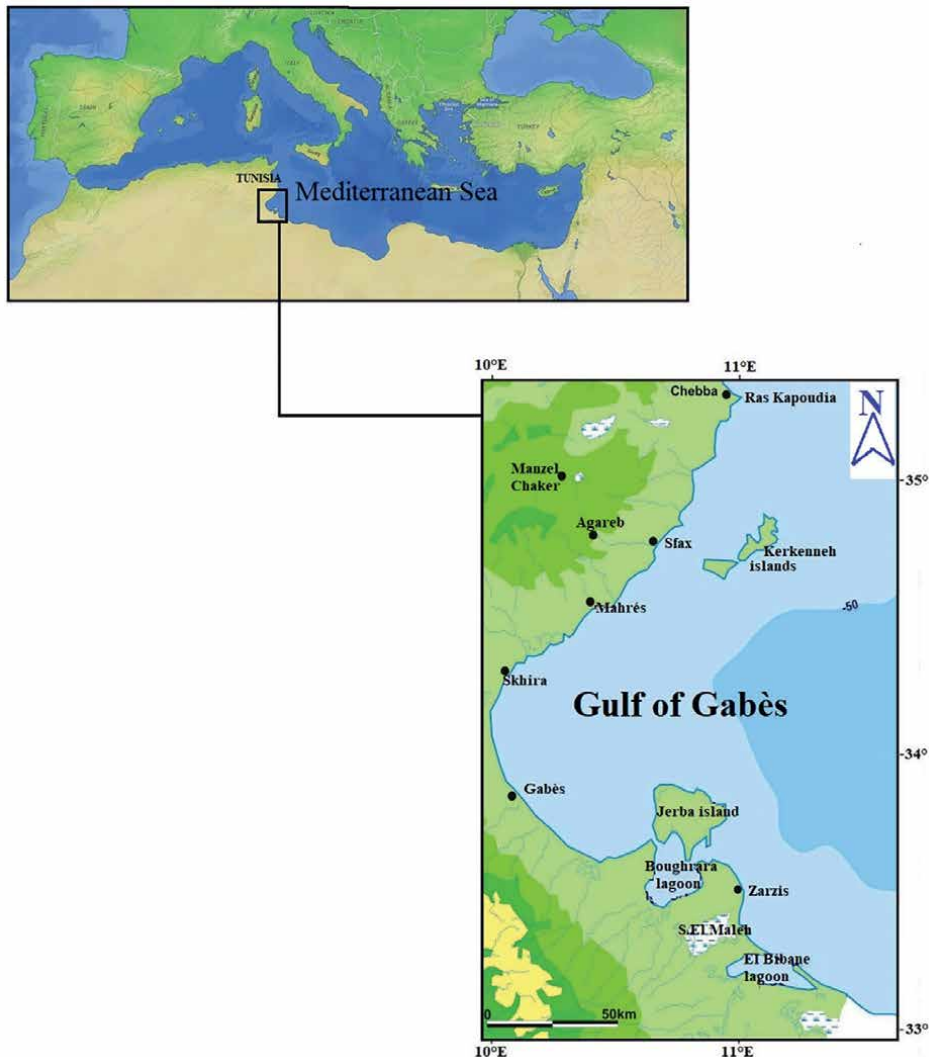


Figure 1.
Localization of the Gulf of Gabès.

While phosphorus is an essential element in the marine ecosystem, its excessive enrichment poses various challenges to biota, elevates the growth of organic matter, and consequently reinforces eutrophication [31, 32]. The high availability of inorganic phosphate along the coast of Gabès is also associated with agricultural use of land along the coast [33]. For phosphates, eutrophication is identified by phosphate levels exceeding $0.68 \mu\text{mol l}^{-1}$ [34]. Very high concentrations of phosphates are recorded in coastal areas of the Gulf of Gabès and reflect a eutrophic state. In fact, phosphate concentrations ranged from 0.51 to $8.52 \mu\text{mol L}^{-1}$ (mean \pm SD = $2.98 \pm 2.44 \mu\text{mol L}^{-1}$) in the southern coast of Sfax [35]. They fluctuated between 1.25 to $2.97 \mu\text{mol L}^{-1}$ (mean \pm SD = $2.07 \pm 0.62 \mu\text{mol L}^{-1}$) in the northern coastal area of Sfax [36]. In the coastal waters of Gabès, phosphate concentrations ranged from 1.7 to $6.7 \mu\text{mol L}^{-1}$ (mean \pm SD = $3.74 \pm 1.65 \mu\text{mol L}^{-1}$) [17].

	Southern coast of Sfax [35]	Northern coast of Sfax [36]	Coast of Gabès city [17]
Ammonium ($\mu\text{mol L}^{-1}$)	3.47–38.06 (13.26 \pm 1.85)	2.99–7.75 (5.01 \pm 1.71)	2.8–20.6 (8.73 \pm 5.41)
Nitrates ($\mu\text{mol L}^{-1}$)	1.09–26.53 (7.56 \pm 1.5)	1.71–11.44 (3.07 \pm 2.95)	3.1–6.0 (0.6 \pm 0.1)
Nitrites ($\mu\text{mol L}^{-1}$)	0.02–4.83 (0.82 \pm 1.29)	0.04–2.64 (0.37 \pm 0.8)	0.4–0.7 (3.07 \pm 2.95)

Eutrophication is recognized for ammonium when values are above 2.2 $\mu\text{mol L}^{-1}$ [34].
Eutrophication is recognized for nitrates when values are above 1.19 $\mu\text{mol L}^{-1}$ [34].

Table 1.

Minimum, maximum and mean values of dissolved inorganic nitrogen forms in the Gulf of Gabès \pm standard deviation from previous studies.

The application of an Eutrophication Index (E.I.) [37] was used by [17] in order to assess the eutrophication status of the coastal waters of Gabès. This index takes into consideration nitrites, nitrates, ammonium, phosphates and Chlorophyll-a. If E.I. is above 1.51, water quality is bad. Values of E.I. calculated in the Gulf of Gabès were > 2.16 , indicating a high ecological alteration of the marine ecosystem [17].

Ammonium stands out as the predominant form of dissolved inorganic nitrogen, followed by nitrates, in the coastal waters of the Gulf of Gabès [17, 35, 36]. This dominance is a typical characteristic of untreated anthropogenic wastewater input [38].

The range (min–max) and mean values of dissolved inorganic nitrogen forms (ammonium, nitrates and nitrites) recorded in the Gulf of Gabès are given in **Table 1**, confirming the widespread status of eutrophication in the coastal waters of the Gulf of Gabès.

4. Signs of eutrophication in the Gulf of Gabès

Eutrophication yields a range of consequences impacting water quality, ecosystems, human health and economic activities [39].

Changes in coastal ecosystem states due to coastal eutrophication include:

- Presence of low dissolved oxygen and formation of hypoxic or “dead” zones (oxygen-depleted waters) particularly on the bottom [6, 40]. Hypoxia and anoxia significantly affect living resources and can cause severe damage to fisheries [41].
- A shift in the composition of phytoplankton species toward more tolerant and opportunistic species [42], creating favorable conditions for the proliferation of harmful algal blooms [43].
- A decrease in zooplankton diversity [44] as larger-sized taxa are replaced by smaller ones [45, 46].
- Loss of marine biodiversity of the aquatic community [47, 48] and the dominance of gelatinous organisms [49, 50].

- A reduction in subaquatic vegetation due to excessive macroalgae and microalgae growth reduces light penetration [40, 51].

The Gulf of Gabès has exhibited these characteristic signs of eutrophication exacerbated by trace metals pollution over the last decades.

4.1 Degradation of water quality in the Gulf of Gabès

The seawater temperature range from 13°C during winter to 26°C in the summer [52]. The mean annual salinity is notably high, around 38 psu, and may surpass 39 psu during summer [53]. The lowest recorded salinity (36 psu) and pH (7.6) were observed in the spring in areas adjacent to discharges from TCG and urban wastewaters [17].

Various studies have highlighted deteriorations in water quality, including turbidity [18, 30, 54] and depletion in seawater oxygen levels [30, 55].

4.2 Decline of *Posidonia oceanica* in the Gulf of Gabès

The characterization and evaluation of specific responses to eutrophication in seagrasses offer a valuable tool for detecting changes in water quality in coastal areas, especially considering they are among the most widespread organisms in coastal waters [56, 57]. Eutrophication has been cited as a primary factor leading to the global decline of seagrass populations [58]. Therefore, *Posidonia oceanica* is suggested for use as a bioindicator to assess the health status of coastal habitats [59, 60]. The surface alkaline phosphatase activity in the seagrass *P. oceanica* can be used as a biomarker of eutrophication [57].

At the beginning of the twentieth century, the littoral beds of the endemic Mediterranean seagrass *P. oceanica* almost entirely covered the sea floor in Gulf of Gabès [61]. However, the present condition of *P. oceanica* indicates an ongoing decline in its meadows and its localized disappearance from multiple areas within the central part of Gabès Gulf [62]. Consequently, a noticeable decline in associated fish production has been consistently observed since 1990 [63]. The loss of the native vegetation cover in the Gulf of Gabès is estimated at 90%, with the *P. oceanica* beds being replaced by the opportunistic green algae *Caulerpa prolifera* in deeper zones [64]. This decline is a global phenomenon and is supposed to be primarily induced by eutrophication [65]. In addition to the effects of eutrophication, the warming of the sea may lead to synergistic effects and an increased rate of loss for these valuable ecosystems [66, 67]. The decline of *P. oceanica* in the Gulf of Gabès is linked to pollution from the phosphate industries [33, 62].

4.3 Phytoplankton and harmful microalgae blooms in the Gulf of Gabès

In the coastal region of the Gulf of Gabès, the phytoplankton community is composed of seven major groups: Dinophyceae (108 taxa), Bacillariophyceae (58 taxa), Cyanobacteria (5 taxa), Dictyochophyceae (1 taxon), Euglenophyceae (1 taxon), Coccolithophoridae (1 taxon) and Chlorophyceae (1 taxon) [68]. Within the identified species, ten have been recognized as potentially toxic, including *Alexandrium minutum*, *Coolia monotis*, *Karenia selliformis*, *Protoceratium reticulatum* [68], *Amphidinium carterae*, *Dinophysis caudata*, *Prorocentrum lima*, *Prorocentrum minimum*, *Pseudonitzschia* sp. [17] and *Ostreopsis* cf. *ovata* [69].

Since 1990, multiple blooms of toxic dinoflagellates have been detected in the Gulf of Gabès [70–73]. Harmful algal blooms (HABs) of *A. minutum* formed in areas subjected to anthropogenic eutrophication such as Sfax Harbor and in confined lagoons in the Gulf [71]. The sudden *A. minutum* blooms along the nearshore of the Gulf of Gabès are complex, but phosphorus appears to be the key driving factor [71].

In 1994, *K. selliformis* was responsible for a significant intensive fish kill, estimated at 200 tons in the Gulf of Gabès [74, 75]. The occurrence of this taxon in the Gulf is related to high nitrate levels and is supported by elevated temperatures [76]. Typically, late summer and autumn are the periods of high bloom frequency of this taxon [70].

The abundance of Cyanobacteria in the Gulf of Gabès was positively correlated with inorganic nitrogen [70]. Blooms of *Trichodesmium erythraeum* were initially observed in July 1988 [77]. *T. erythraeum* blooms occurred approximately 2.11 times per year during the period from 1988 to 2013 [78]. Damages resulting from the toxic algal blooms cannot be considered resolved by reducing their populations. Indeed, numerous toxic Dinophyceae produce cysts at their blooming, successively accumulating in the sediments where they wait for the return of favorable conditions to germinate [79]. The encystment phenomenon is regular and frequent in the Gulf of Gabès but affects a low variety of species. During two decades of monitoring, eight different groups of cysts were recorded in the Gulf, with the dominance of ones of potentially toxic species [80, 81]. Even in the absence of algal inoculation from neighboring geographic areas, such toxic species can re-appear by the germination of the cysts in the sediments each time the conditions are favorable. Thus, the management of coastal areas has to carefully consider this “potential” harmful injection, even in the absence of algal blooms in the water column for many years.

4.4 Copepoda in the Gulf of Gabès

Zooplankton assemblages in the Gulf of Gabès were primarily dominated by copepods, accounting for 69–83% of the total zooplankton abundance [82]. A total of 52 species of Calanoida, 30 Cyclopoida and 11 Harpacticoida species were reported in the Gulf of Gabès [83, 84]. Notably, Cyclopoida, particularly Oithonidae (mainly *Oithona nana*), dominated copepod communities in the Gulf of Gabès [17, 35, 36, 82, 85]. We suggest that with increasing eutrophication over decades, a general shift to smaller-sized Copepoda with egg sacs, particularly the cyclopoid *Oithona nana*, was observed in the Gulf of Gabès. The success of *Oithona* spp. in eutrophicated and disturbed ecosystems is mainly due to their remarkable adaptability to changing environments than other species [86] as they are typical ecological generalists [83, 84]. In fact, the dominance of this species can be linked to a change in the food spectrum (and/or the fact that it does not spawn eggs into the water column). The possession of egg sacs is considered as an advantage in eutrophicated ecosystems that evolve hypoxic/anoxic bottom waters [7]. Spawned eggs that fall into the sediments may be prevented from hatching due to reduced oxygen levels. Therefore, the combination of a successful reproductive strategy, an omnivorous diet, and lower metabolic demands likely underlines the prominence of *Oithona* in the Gulf of Gabès [85, 87].

5. Conclusion

As documented by a number of investigations, eutrophication is a serious problem for the biodiversity in the Gulf of Gabès. However, since the Gulf also experienced

chemical pollution by trace metals, and overfishing, eutrophication may not have been the only factor. The enrichment of nutrients, especially phosphorus, interacts with these factors and, in addition, with climate change. Due to cumulative anthropogenic pressures, integrated management of the coastal marine environment of the Gulf of Gabès remains necessary to re-direct the ecosystem functioning toward a healthier status and a restoration of ecosystem services [88, 89] possibly compromised. Efforts in the Gulf of Gabès to contain eutrophication involve a policy of environmentally sustainable development, with tighter industrial regulations, enhanced agriculture and improved wastewater management. The heavy socio-economic impact of such a policy is only apparent. In fact, the decision should be sustained by detailed studies on the economic convenience of such an approach, with a precise monetization of what the present situation subtracts in terms of ecosystem services to society. The restoration of good environmental status, in addition, would not be a cost for managers because open gulfs (such as the Gabès one) should be easily re-populated. Living organisms, in fact, can go elsewhere when local conditions are adverse or can undergo a lethargic condition, waiting for the return of suitable conditions in the sediments for years [90, 91]. The re-covering of a good environmental status (and the re-launch of ecosystem services) could be, consequently, a fast process.

Author details

Neila Annabi-Trabelsi^{1*}, Mohammad Ali², Genuario Belmonte^{3,4}, Habib Ayadi¹
and Wassim Guerhazi¹

1 Marine Biodiversity and Environment Laboratory (LR18ES30), University of Sfax, Sfax CP, Tunisia

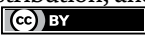
2 Environment and Life Sciences Research Center, Kuwait Institute for Scientific Research, Safat, Kuwait

3 Laboratory of Zoogeography and Fauna, Department of Biological and Environmental Sciences and Technologies, University of Salento, Lecce, Italy

4 National Biodiversity Future Center NBFC—CNR, Palermo, Italy

*Address all correspondence to: neila.trabelsi@isbs.usf.tn

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Chapter 2

Biostimulant Properties of Marine Bioactive Extracts in Plants: Incrimination toward Sustainable Crop Production in Rice

Melekote Nagabhushan Arun, Rapolu Mahender Kumar, Sailaja Nori, Banugu Sreedevi, Guntupalli Padmavathi, Pallakonda Revathi, Neha Pathak, Dayyala Srinivas and Raman Meenakshi Sundaram

Abstract

Enhancing productivity through integrated and comprehensive nutrient management is pertinent to sustainable intensification of agricultural ecosystems. The utilization of marine bioactive stimulants has been gaining momentum and impetus in crop agricultural farming system due to their phytoelicitor activity. Liquids biostimulants derived from seaweed evoke defense responses in plants that contribute to resistance to abiotic stresses and challenges like high temperature, salinity, moisture stress, and cold. Seaweed extracts are immensely organic and suitable for growing crops that are both organic and environmentally friendly. Seaweeds provide an abundant source of natural growth substances that can be employed to enhance plant growth. Seaweeds are one of the most significant marine resources of the world, and derived compounds have been extensively used as amendments in crop production systems due to the presence of macronutrients such as Ca, K, and P and micronutrients like Fe, Cu, Zn, B, Mn, Co, and Mo, presence of several plant growth stimulating compounds including cytokinin, auxins, gibberellins, and betaines which are essential for plant growth and development. The purpose of the current chapter is to explore the functional and growth characteristics induced by seaweed extracts in addition to their modes and mechanisms of action in rice crops, which are responsible for elicitor and phytostimulatory activities and boost in grain production and nutrient usage efficiency.

Keywords: seaweed extract, macroalgae, liquid biostimulants, stress tolerance, sustainable agriculture, phytoelicitor compounds

1. Introduction

Abiotic and biotic stresses restrict the growth and productivity of crops. The global effects of negative climatic changes have manifested as desertification, escalate atmospheric CO₂, temperature, and soil salinization, and nutrient imbalances like mineral toxicity and deficiency have caused dramatic effects on agricultural production and the quality of crops. Abiotic stresses have reduced the growth, development, productivity, and quality of plants and local extinction of species. The global amount of cultivable land for agriculture is continuously shrinking due to adverse effects of climate change. Abiotic stresses may be prevented by optimizing plant growth conditions and through provision of water, plant growth regulators (PGRs – auxins, cytokinins, gibberellins, stringolactones, and brassinosteroids) and nutrients. Rice is one of the most significant food crops grown across the world. It is a primary staple food for more than 50% of the world's population, accounting for more than 20% of their daily caloric consumption from rice [1]. Rice is cultivated in 160 million ha area globally with an average yield of 4631 kg ha⁻¹ [2].

Biostimulants are increasingly being incorporated into production system with the objective of altering physiological processes in plants to optimize plant productivity [3]. Biostimulants present a potentially novel approach for regulating and altering physiological processes in plants to stimulate growth, to mitigate stress limitations, and to boost yield. Biostimulant materials are natural products which contain no added chemicals or synthetic plant growth regulators and which have a beneficial effect on plant growth. Seaweed/sea plants are gaining considerable importance due to the distribution, renewable nature, and widespread application [4]. Organic biostimulants are compounds which increase plant growth and vigor through increased efficiency of nutrient and water uptake. Plant biostimulants are compounds when applied to plants, seeds, or growing substrates have the capacity to modify physiological processes of plants in a way that provides potential advantages to growth and stress response. Seaweed (macroalgae) is a multicellular macroscopic algae species which are subdivided into red, green, and brown algae due to their pigmentation according to phyla, Rhodophyta, Chlorophyta, and Phaeophyceae. Nine thousand species of macroalgae are broadly classified into three main groups, viz. Rhodophyta (red algae), Ochrophyta-Phaeophyceae (Brown algae), and Chlorophyta (green algae), based on pigments present. Sea plant biostimulants derived from natural raw resources are used in the ultrasmall and minute doses for modification of biochemical and physiological plant processes with the objective of more complete realization of genetic potential of their productivity due to changes in hormonal status, activation of metabolic processes, increase in nutrient efficiency, stimulation of growth, development, and strengthening of the potential to withstand the negative effects of various stress factors. Seaweed biostimulants are new class of inputs offering a potential alternative to traditional organic chemical inputs and can reduce the application of fertilizers to improve soil health and increase soil microbial activity [5]. Chemical analysis of seaweeds and their extracts have revealed the presence of a broad spectrum of plant growth regulators/phyto-hormones such as auxins, gibberellins, cytokinins, and betaines, enzymes, vitamins and hydrolyzed proteins, polysaccharides, nutrients, and trace elements (Fe, Cu, Zn, Co, Mo, Mn, and Ni) in varying amounts and biologically active alginic acids, polyphenols, and free amino acids which invigorate plant growth and alleviating several biotic and abiotic stresses [6]. Seaweeds often contain larger concentrations of Ca, K, Mg, Na, Cu, Fe, and Zn than terrestrial plants [5]. The biostimulant aids in fostering the development of beneficial

soil microorganisms, developing tolerance to environmental stress and improving nutrient uptake from soil and enhancing antioxidant properties. Seaweed extract supplement improved significantly the content of nitrate nitrogen (N), available phosphorus (P), and available potassium (K) in rhizosphere soil in the tillering stage, and, finally, increased the rice yield and quality mildly in rice crop.

Biostimulants are agents which at very low concentrations improve the basic biochemical processes in plants and soil and thereby improve the growth and development of plants and increase resistance to stress. The seaweed properties with most potential relevance to crop production involve elemental composition (e.g. primary plant nutrients, other nutrient elements, heavy metals, and salts) and organic compound composition (e.g. energy sources for microbial processes). Seaweed extracts improved the number and size of chloroplasts, the growth of chloroplast grana, and the concentration of chlorophyll in leaves due to the presence of beneficial amounts of cytokinins, auxins, betaines, and inorganic salts [7]. The most commonly used seaweed as a biostimulant is an alga, obtained from North Atlantic Ocean and known as *Ascophyllum nodosum*, rich in polysaccharides (alginate, fucoidan, and laminarin), minerals, and vitamins [8]. The goal of the chapter is to provide comprehensive analysis of the current situation in the field of biostimulants and to develop a science-based theoretical foundation for the conceptualization, classification, and practical application of sea plant biostimulants. The structure of the chapter is based on the consideration of biostimulants in terms of the action on different regulatory and functional system of plants (signaling, metabolism, uptake, and transport system) using both conceptual and methodological approaches.

2. Different types of seaweed/plants and its distribution

The seaweeds are distributed horizontally in different zonation, viz. supratidal (supra-littoral), intertidal (littoral) and subtidal (sub-littoral) regions of the seas and oceans. Green seaweeds are most commonly found in the intertidal zone (**Table 1**). Common green seaweeds are species of *Ulva* (sea lettuce), *Enteromorpha* (green string lettuce), *Chaetomorpha*, *Codium*, and *Caulerpa*. Brown seaweeds inhabit in the tidal or upper subtidal zone. Common brown seaweeds are species of *Sargassum*, *Laminaria*, *Turbinaria*, and *Dictyota*. Red seaweeds grow in subtidal waters. Common red seaweeds are species of *Gracilaria*, *Gelidiella*, *Eucheuma*, *Ceramium*, and *Acanthophora*. The blue green algae grow in supra-tidal region mostly as colonies, and sometimes they occur as epiphytes on other algae. Common blue green algae are species of *Lyngbya*, *Spirulina*, and *Oscillatoria*. Seaweeds, which are multicellular, microscopic plants that are found coastal locations, are an integral component of coastal marine ecosystems. Marine algae or seaweeds are classified into three taxonomic groups that have diverse pigment composition: Rhodophyta (red algae), Chlorophyta (green algae), and Ochrophyta (brown algae). The Indian Ocean is host to 865 species of seaweed belonging to 216 genera and 68 families [9]. Brown algae (Phaeophyceae) are the largest prevalent type of seaweed that are habitat to water of temperate region where more than 2000 species are found. Green algae (Chlorophytta) can be found in marine or freshwater habitats, and some even thrive in moist soils where more than 1800 species are found. Green algae come in three forms: unicellular, colonial, or multicellular. Sea lettuce (*Ulva lactuca*) is a type of green algae commonly found in tidal pools. Red seaweed (Rodophyta) is the largest group of algae in the plant kingdom which account more than 7200 species

Class	Order	Family	Species
Rhodophyceae (Red algae)	Ceramiales	Ceramiales	<i>Spyridia filamentosa</i> <i>Ceramium planum</i>
		Rhodomelaceae	<i>Amansia glomerata</i> <i>Laurencia papillosa</i> <i>Acanthophora spicifera</i> <i>Laurencia johnstonii</i> <i>Laurencia obtusa</i>
	Corallinales	Lithophyllaceae	<i>Amphiroa rigida</i> <i>Amphiroa gracilis</i>
		Mastoporaceae	<i>Mastophora rosea</i> <i>Mastophora pacifica</i> <i>Mastophora multistrata</i>
		Corallinaceae	<i>Corallina elongate</i> <i>Janie rubens</i> <i>Lithothamnium calcareum</i>
	Nemaliales	Galaxauraceae	<i>Galaxaura apiculata</i> <i>Galaxaura fastigiata</i> <i>Galaxaura filamentosa</i> <i>Actinotrichia fragilis</i>
		Acrochaetaceae	<i>Porphyra perforate</i>
	Cyanidiales	Cyanidiaceae	<i>Cyanidium caldarium</i>
	Gelidiales	Gelidiaceae	<i>Gelidium serrulatum</i>
	Gracilariales	Gracilariaceae	<i>Gracilaria edulis</i> <i>Gracilaria gracilis</i> <i>Gracilaria salicornia</i> <i>Gracilaria textorii</i> <i>Gracilaria verrucos</i> <i>Gracilaria dura</i>
	Gigartinales	Solieriaceae	<i>Eucheuma denticulatum</i> <i>Eucheuma spinosum</i> <i>Kappaphycus alvarezii</i> <i>Kappaphycus cottonii</i> <i>Sarcodiotheca chordalis</i>
		Cystocloniaceae	<i>Hypnea spinella</i> <i>Hypnea musciformis</i>
	Phaeophyceae (Brown algae)	Dictyotales	Dictyotaceae
Ectocarpales		Scytosiphonaceae	<i>Hydroclathrus clathratus</i> <i>Hydroclathrus minutus</i>
Fucales		Sargassaceae	<i>Sargassum cristaefolium</i> <i>Sargassum polycystum</i> <i>Cystoseira humilis</i>
		Fucaceae	<i>Ascophyllum nodosum</i> <i>Fucus gardneri</i> <i>Fucus spiralis</i> <i>Fucus vesiculosus</i>
		Alariaceae	<i>Alaria esculenta</i>
		Durvillaeaceae	<i>Durvillea Antarctica</i> <i>Durvillea protatorum</i>
Laminariales		Lessoniaceae	<i>Ecklonia maxima</i> <i>Nereocystis luetkeana</i>
		Laminariaceae	<i>Laminaria digitata</i> <i>Macrocystis pyrifera</i>

Class	Order	Family	Species
Ulvophyceae (Green algae)	Bryopsidales	Caulerpaceae	<i>Caulerpa paspaloides</i> <i>Caulerpa lentillifera</i> <i>Caulerpa racemosa</i> <i>Caulerpa serrulata</i> <i>Caulerpa sertularioides</i>
		Halimedaceae	<i>Halimeda cuneata</i> <i>Halimeda cylindracea</i> <i>Halimeda discoidea</i> <i>Halimeda incrassata</i> <i>Halimeda macroloba</i> <i>Halimeda opuntia</i> <i>Halimeda tuna</i>
		Udoteaceae	<i>Udotea geppiorum</i>
		Dichotomosiphonaceae	<i>Avrainvillea erecta</i> <i>Avrainvillea lacerata</i>
		Codiaceae	<i>Codium ovale</i> <i>Codium bursa</i> <i>Codium liyengarii</i> <i>Codium tomentosum</i>
	Cladophorales	Cladophoraceae	<i>Chaetomorpha crassa</i> <i>Chaetomorpha spiralis</i> <i>Cladophora rupestris</i>
		Anadyomenaceae	<i>Anadyomene wrightii</i> <i>Microdictyon marinum</i>
		Siphonocladaceae	<i>Boergesenia forbesii</i> <i>Dictyosphaeria cavernosa</i>
		Valoniaceae	<i>Valonia aegagropila</i> <i>Valonia fastigiata</i>
	Dasycladales	Dasycladaceae	<i>Bornetella sphaerica</i> <i>Neomeris annulata</i>
Ulvales	Ulvaceae	<i>Ulva prolifera</i> <i>Ulva armoricana</i> <i>Ulva fenestrata</i> <i>Ulva lactuca</i> <i>Ulva rigida</i> <i>Enteromorpha prolifera</i>	
Ulotrichales	Monostromataceae	<i>Monostroma grevillei</i>	
	Ulotrichaceae	<i>Spongomorpha aeruginosa</i>	
Prasiolales	Prasiolaceae	<i>Prasiola calophylla</i>	

Table 1.
 List of important seaweed species.

found in shallow waters and withstand deep water and low light conditions. It has been reported that 59 species of seaweeds found in Indonesian coastal region, 15 of the species are capable of stimulating germination, development, growth, and production of rice and legume crops [10]. *Halimeda opuntia*, *Caulerpa racemosa*, *Gracilaria edulis*, and *Chaetomorpha crassa* grow widely and abundantly in stagnant water in the mangrove hinterlands of Indian and Pacific Ocean. The seaweeds easily grow, survive, and monopolize in stagnant water where the salinity and temperature greatly fluctuate. *Hypnea musciformis* is found in Atlantic, Pacific, and Indian Ocean and has the widest geographical distribution. *Mastophora rosea*, *Mastophora pacifica*, and *Mastophora multistrata* were found in bluish purple color and distributed in Pacific Ocean and Indian Ocean. *Sarcodiotheca chordalis* was reported in

the Mediterranean Sea and Atlantic Ocean from Morocco to Southwest England. *Cheilosporum cultratum* and *Caulerpa lentillifera* have been newly found in near the islands of Indian Ocean. Totally 59 species of seaweeds were recorded from the Indian Ocean which included six species of Scytosiphonaceae and Gracilariaceae, five species of Ulvaceae, four species of Cladophoraceae and Halimedaceae, three species of Dictyotaceae, two species of Caulerpaceae, Rhodomelaceae, Corallinaceae, Florideophyceae, Sargassaceae, Cystocloniaceae Gelidiellaceae, and Oscillatoriaceae, and one species of Bangiophyceae, Lithophyllaceae, Codiaceae, Cystocloniaceae, Characea, Valoniaceae, Boodleaceae, Siphonocladaceae, Solieriaceae, Galaxauraceae, Liagoraceae, Sphacelariaceae, Monostromataceae, Ulvophyceae, and Lessoniaceae [11]. *Kappaphycus alvarezii* is a tropical seaweed being cultivated in southeast coast-line of India since more than a decade for the extraction of thickening agent called kappa-carrageenan using traditional farming systems.

3. Significance of seaweed in agriculture

Liquid products based on marine algae were introduced in 1950 and now are successfully used worldwide. The seaweed concentrates are administered to crops as root dips, soil drenches, and foliar sprays. Seaweed-derived biostimulant extracts used as foliar sprays have gained importance for multiple crops including various grasses, cereals, pulses, and vegetables [12]. Seaweed extract application as foliar spray is a common practice to boost production in many commercial crops. Seaweed extract enhances tolerance against environmental stresses and challenges and enhances nutrient uptake from soil by plants [13]. Foliar application of seaweed biostimulants offers a quicker method of supplying nutrients to higher plants alternate to soil application method [14]. This may be as a result of active nutrient uptake through stomatal pores instead of cuticular uptake [15]. The mechanism by which seaweed biostimulants affect cellular metabolism is based on the physiological action of macro- and microelements, amino acids, vitamins, and substances. The seaweed biostimulant enhances meristematic growth, translocation of photosynthates, enzyme activation, cell elongation, and cell stability [16]. Seaweed extract enhances chlorophyll content by increasing the biogenesis of chloroplasts and reducing chlorophyll degradation, which was due to the upregulated genes associated with photosynthesis, cell metabolism, stress response, and S and N metabolism in *Brassica napus* L. [17]. The seaweed when applied to crops as foliar spray can accelerate the rate of cell division and elongation. Seaweed extract of the brown algae *Sargassum heterophyllum* contain cytokinin, while *Ascophyllum nodosum* contain the growth hormone Indole-3-acetic acid. Seaweed supplies macro- and micronutrients, has liming properties, and increases phosphorus availability, the phycocolloids improve soil structure, increases the water retention and cation-exchange capacities of soil, binds metals, boosts biological activity, and improves plant resistance to aggressive biotic and abiotic agents [18].

4. Seaweed extract on biochemical characters in crops

The bioactive compounds (not yet fully elucidated) present in *Ascophyllum nodosum* extracts when applied to stressed plants have reduced the deleterious effects of drought stress by regulating a series of sequential molecular, cellular, and physiological responses including the modulation of several genes, resulting in an

Parameters	<i>Ascophyllum nodosum</i>	<i>Laminaria digitata</i>
Type	Brown	Brown
Water (%)	70–80	73–92
Ash (%)	15–26	21–37
Alginic acid (%)	15–35	20–50
Laminaren (%)	0–15	0–20
Mannitol (%)	5–10	4–20
Fucoxanthin (%)	4–15	2–6
Carbohydrate (%)	10	1–3
Protein (%)	5–10	8–20
Fat (%)	2–8	1–3
Tannins (%)	2–12	1–2
Potassium (%)	2–3	1.3–3.8
Sodium (%)	3–4	0.9–2.2
Magnesium (%)	0.5–0.9	0.5–0.8
Iodine (%)	0.01–0.1	0.3–1.3

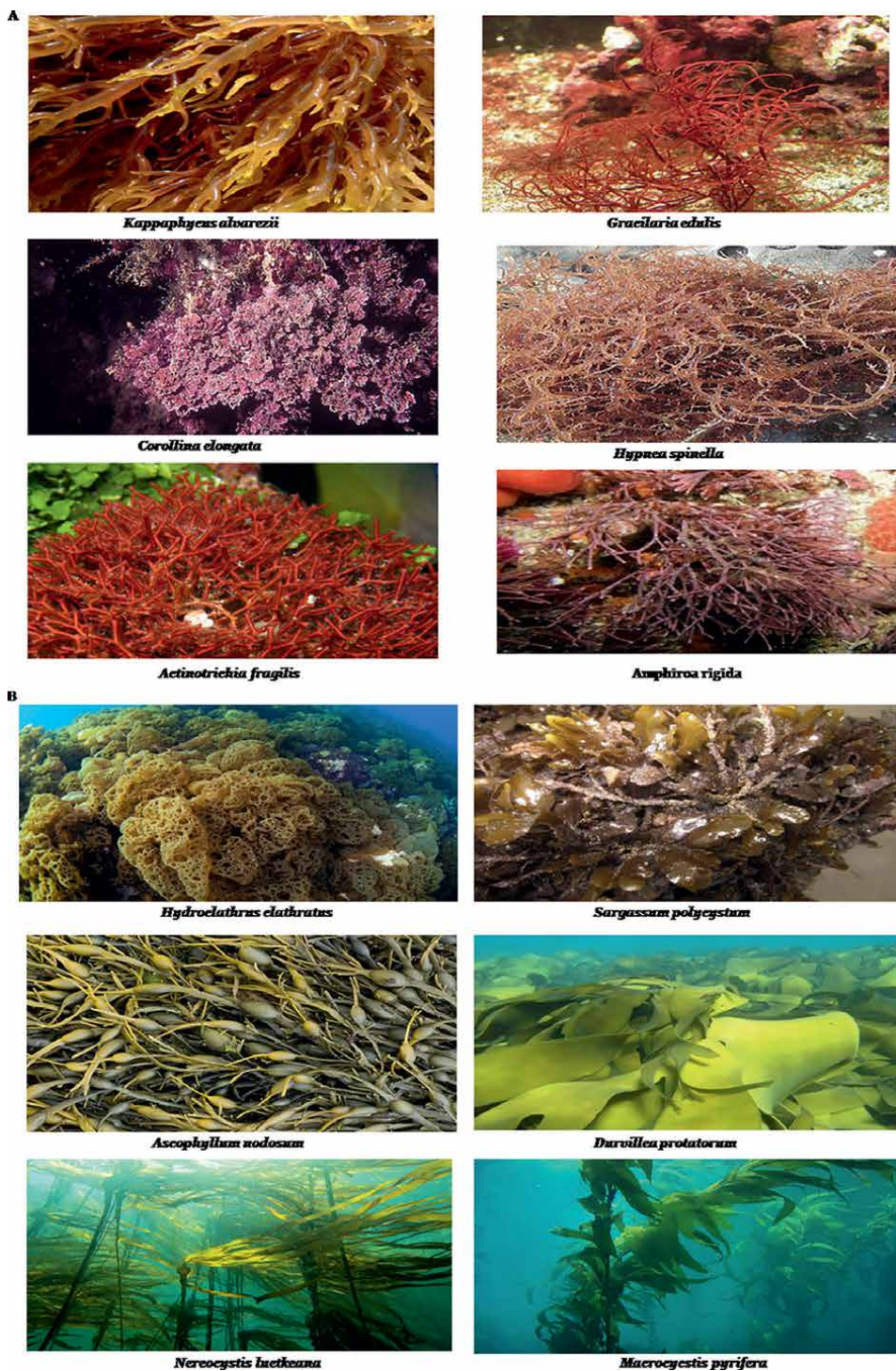
Table 2.
 Chemical composition (in percentage) of the seaweeds *Ascophyllum nodosum* and *Laminaria digitata*.

accumulation of various osmolytes, an improved antioxidant system, and enhanced gaseous exchange through stomatal regulation (Table 2). Priming wheat seeds with the extracts of *U. linza* or *C. officinalis* promoted almost physiological parameters like chlorophyll, carotenoids, sugars, proteins, and lipids. Seaweed extracts with high magnesium and mineral content tended to increase leaf total chlorophyll and carotenoids concentration [19]. The increased protein and sugar contents due to seaweed priming could be attributed to absorption of majority of the major elements in these extracts, particularly magnesium, which could have activated chlorophyll synthesis and, as a result, improved photosynthetic rates [20]. Foliar spray of seaweeds extract was effective in improving wheat performance by enhancing compatible osmolytes and antioxidant compounds and enhancing variation among non-coding chloroplast DNA (cpDNA) regions trnL intron and psbA-tnH as a response to water deficit.

5. Physiological effect of seaweeds extracts application in mitigating abiotic stress

Application of seaweed extracts as natural regulators has had promising benefits, such as enhanced crop productivity and plant vigor to withstand adverse environmental influences. Plants, being sessile, are relentlessly challenged by a variety of environmental stresses that limit their growth and productivity. Due to the complex metabolic pathways involved in stress tolerance, limited success has been achieved in generating stress-tolerant crops through genetic engineering. Extract of *Ascophyllum Nodosum* application has shown to assist soybean plants endure severe drought conditions by regulating leaf temperature, turgor, and several stress-responsive genes [21]. Mild salinity stress causes physiological drought in plants, impairing

cell–water relations, inhibiting cell expansion, and, consequently, reducing growth rate. Soil salinity is a global problem, affecting over 800 million hectares of land, resulting in massive impacts on agricultural productivity [22]. Long-term exposure



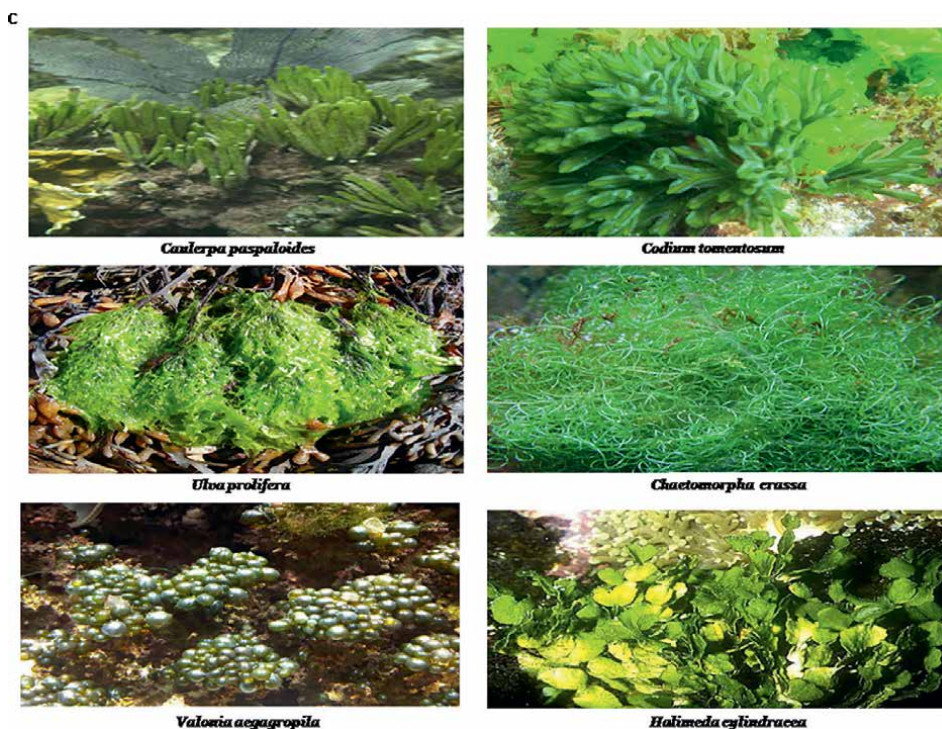


Figure 1. Common seaweeds species in Ocean (A), Rhodophyceae (Red algae), (B) Phaeophyceae (Brown algae), and (C) Ulvophyceae (Green algae).

to high salinity causes ionic stress by disturbing the homeostasis of intracellular ions, which results in membrane dysfunction and attenuation of metabolic activity and secondary effects, inhibiting growth and inducing cell death [23]. Mild salinity stress induces physiological drought in plants, impairing cell–water relations, inhibiting cell expansion, and consequently, reducing growth rate. Salinity induces both ionic and osmotic stresses, thus reducing plant growth and productivity [24]. *Ulva prolifera* extract reduced the oxidative damage caused by drought not only by activating the antioxidative system but also by providing essential hormones and minerals for wheat growth [25]. Drought stress is one of the most severe abiotic stresses which have negative impact on plant growth, crop production, and numerous metabolic processes. Application of seaweed extract in mitigating water stress and adverse effects is highly important for plant production (Figure 1).

6. Effect of seaweed extract on crop development and yield

Seaweed extract (15 percent) was sprayed as foliar application to rice crop during vegetative and generative stages. The results shown that extracts of *Sargassum calophyllum*, *Sargassum polyceratum*, *Sargassum vulgare*, *Sargassum aquifolium*, *Sargassum polycystum*, *Hydroclathrus clathratus*, *Hydroclathrus minutes*, *Ulva fasciata*, *Ulva ferticulata*, *Padina pavonica*, *Gracilaria edulis*, *Chaetomorpha crassa*, *Turbinaria ornata*, and *Turbinaria murayana* were able to promote growth of rice plants. *Hydroclathrus clathratus* extract enhanced crop growth and production of rice crop. This phenomenon

may be due to the presence of active compounds and micro- and macronutrients in the extract of seaweeds which can stimulate plant growth (**Figure 2**). Various species of marine algae found in nature contain organic compounds which activities resemble the activity of cytokinins, auxins, and gibberellins. The organic compounds were able to stimulate growth as a result of enhancement of protein synthesis, cell division, and mobilization of nutrients needed to boost growth of rice crop [9].

Seaweed extract supplement of *Sargassum horneri* was applied at 5 percent to fertilizer (50 percent) as basal and top dressing increased the rice yield slightly and, especially, the amount of fertilizer applied was saved by 50% in rice crop [26]. Three foliar sprays of *Kappaphycus alvarezii* (K sap) and *Gracilaria edulis* (G sap) when applied at the doses of 2.5, 5.0, 7.5, and 15.0 percent (v/v) coupled with water spray as a control at different phases of the maize crop significantly enhanced grain yield significantly by 18.5 percent and 26.0 percent. The enhancement in yield was correlated to increase in the number of rows in cob, cob length, and 100 grain weight and improved in nutrient uptake [27]. The substantial increase in plant height, root nodules, root volume, number of branches at harvest, dry matter production, chlorophyll content of the leaves, grain yield, grain nitrogen percentage, and grain protein content was significantly recorded by soaking seed in 0.1% seaweed extract solution for 30 minutes + foliar application of seaweed extract (0.25%) twice on 25 DAS and 35 DAS in green gram (single spray). The existence of micro- and macronutrients, trace elements, humic acid, amino acids, plant growth hormones, vitamins, antibiotics, carbohydrates, metabolite boosters, and other organic compounds in seaweed extract significantly enhanced the growth, yield, and quality traits of green gram [28].

Spraying of *Kappaphycus alvarezii* sap (5.0%) in tomato crop significantly increased the root length, shoot length, and yield over (control) plants sprayed with water. The result was due to macro- and microelements as well as growth-promoting components like cytokinin present in seaweed. There was significant increase and

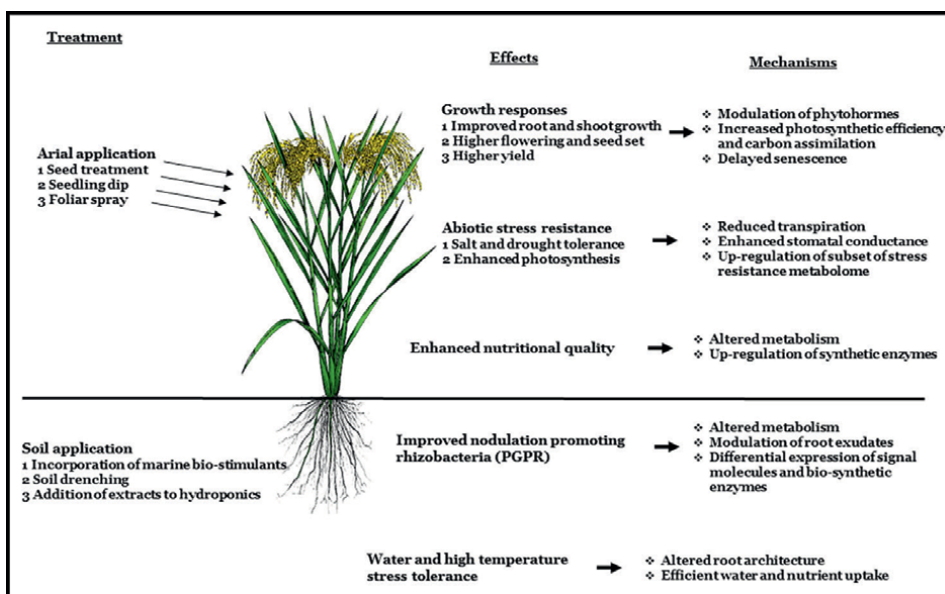


Figure 2. Illustration of physiological effects of elicited seaweed biostimulants and possible mechanisms of bioactivity.

enhancement in chlorophyll and b content in leaves over control where *Kappaphycus alvarezii* was applied (5.0% sap). Enhanced leaf chlorophyll concentration of treated plants with seaweed biostimulant was due to the presence of betaines [29]. Spraying rice crop with seaweed extracts at rate of 2000 ppm led to a significant enhancement in the weight of 100 grains and produced the highest significant values of grains yield per plant under salt stress conditions. The superiority was due to the benefits of seaweed components providing a remarkable source of bioactive substances such as macro- and micronutrients, essential amino acids, fatty acids, vitamins, cytokinins, and auxins like growth-promoting substances influencing plant growth and production by altering cellular metabolism in treated plants. In rice, higher plant height, dry matter production, yield attributes such as number of grains per panicle, panicle length, thousand grain weight, number of productive tillers per m², grain yield, and straw yield were recorded when seaweed extract was applied to the soil at a rate of 12.5 kg/ha along with a foliar spray of seaweed liquid [30]. The application of liquid seaweed extracts improved plant growth and yield characteristics and enhanced soil quality in foxtail millet [31].

Seaweed liquid biostimulant of *Kappaphycus alvarezii* sap when applied as foliar application in rice crop boosted the crop growth characteristics such as plant height, number of leaves plant⁻¹, number of tillers plant⁻¹, and grain yield over recommended dose of fertilizers [32]. Increase in yield is due to higher number of panicles through improved canopy establishment, photosynthesis, translocation of assimilates, better interception of light, and markedly decrease in inter plant competition for soil nutrients and solar energy. Seaweed extracts applied on onion grown under water stress significantly enhanced N, P, and K uptake by 116, 113, and 93% compared to the unsprayed plants [33]. Agronomic characters and yield components of rice in algalized plots increased compared to the treatment with recommended dose of urea [34].

In vitro mass propagation using hypocotyls and leaf disk explants of brinjal (*Solanum melongena* L.) cultivar Pusa Purple Long, the influence of seaweed liquid extracts (SLEs) prepared from *Gracilaria salicornia*, *Padina gymnospora*, *Padina boergesenii*, and *Gelidiella acerosa* on plant growth was studied. The rate of shoot and root induction and the percentage of seed germination were both markedly improved by the use of seaweed liquid extract in MS medium. Plant growth can be promoted by seaweed extracts contain stimulating compounds. Seaweed extracts contain high endogenous levels of micro- and macronutrients, vitamins, cytokinins, auxins, amino acids, gibberellins, and organic acids to enhance the growth of crop plants [35].

Seaweed foliar spray sap of *Kappaphycus alvarezii* and *Gracilaria edulis* at five percent and above concentration boosted grain yield attributes and yield of rice 5.4 to 19.4 percent higher as compared to recommended dose of fertilizers. Soaking of rice seeds in lower concentration (2.5 and 5%) of saps extracted from seaweed improved the germination and seedling vigor of rice [36]. *Padina gymnospora*, *Gracilaria edulis*, and *Ulva fasciata* aqueous extracts applied as a seaweed biofertilizer to promote seed germination of *Capsicum annuum* illustrated higher root and shoot length, mean germination time, germination index, germination percent, seedling vigor index, germination energy, total protein content, total phenol content, and antioxidant inhibition percentage [37]. Seaweed extract of *Sargassum denticulatum* (2 percent) foliar application enhanced all growth and yield parameters and more accumulation of the organic solutes in leaves of water-stressed plants. Application of seaweed biostimulant/extract enhanced seedling growth of wheat plants during growth period [38]. The influence of three red marine algae species (*Laurencia obtusa*, *Corallina elongata*, and *Jania rubens*) was assessed as biostimulant to enhance the growth of maize (*Zea mays* L.) plants. Application

of mixture of *Laurencia obtusa* and *Covallina elongata* enhanced plant fresh and dry weight in maize crop [39]. Seaweed sap foliar application (*Kappaphycus alvarezii* and *Sargassum denticulatum*) at 10 percent at 20–40 DAS and 40–60 DAS revealed maximum accumulate growth rate (AGR), crop growth rate (CGR), and relative growth rate (RGR) over 5 percent and 75 percent along with foliar application water spray in maize. Seaweed extract mainly contains amino acids like betaines and sterols which enhance the photosynthetic activity, N metabolism, and protein synthesis which boost corn production and also the availability of growth regulators to extract especially auxins and cytokinins which are responsible for cell enlargement and inter-nodal elongation and thereby increase the vegetative growth [40]. Application of seaweed extract as foliar at 2 percent concentration enhanced all growth and yield parameters and more accumulation of the organic solutes in leaves of water-stressed crop plants. Low concentrations application of *Ascophyllum nodosum* extracts on the ground or on the foliage of rice caused an increase in chlorophyll content in the leaves. The decrease in chlorophyll degradation, which might be partially attributed to betaine from seaweed extract, resulted in an increase in chlorophyll content and photosynthetic rate [41].

Application of seaweed extract at the rates of 15% K sap or 15% G sap with 100% RDF at 35, 45, and 60 days after transplanting (three distinct intervals) over the required dose of fertilizer enhanced grain yield by 11.80 percent and 9.52 percent, respectively. The growth, yield attributes, grain yield, quality, and chlorophyll content of rice were significantly influenced with foliar spraying seaweed extract on the foliage. In accordance with the results, spraying seaweed extract at 15 percent K sap with 100 percent recommended dose of fertilizer resulted in substantially higher growth, yield attributes, and chlorophyll content over spraying seaweed extract at 15 percent G sap with 100 percent recommended dose of fertilizer. Yield enhancements in seaweed-treated plants are responsible to be associated with the hormonal components present in the extracts, especially cytokinins [42]. The most significant values of grain yield per plant were achieved after spraying wheat plants with seaweed extract at a concentration of 2000 ppm under salt stress conditions. The superiority was induced by the advantages of seaweed components, which function as a predominant source of bioactive compounds like macro- and micronutrients, essential fatty acids, amino acids, vitamins, cytokinins, and auxins, substances that affect cellular metabolism in treated plants and hence promote growth and productivity [43]. Application of seaweed biostimulant at a dose of 2 ml L⁻¹ demonstrated positive impact on the growth, development, yield, and essential oil contents of coriander plant [44].

7. Effect of application of seaweed biostimulant on nutrient uptake

Rhizosphere microorganisms are conducive to soil nutrient cycling for plant growth. Rhizosphere microorganisms contribute to the release of organic acids, amino acids, carbohydrates, and secondary metabolism products in rice fields. Seaweed extracts have been reported to enhance tolerance to environment stress, boost the growth and yield of plants, and promote nutrients availability and nutrients uptake from the soil. Since seaweed extract is the source of organic matter and nutrients, so the utilization of seaweed extract as biofertilizer could balance the N, P, and K deficiencies in paddy soils. Root of rice is a hidden organ in soil that mediates critical functions, involving the uptake and storage of water and nutrients [45]. Rhizosphere microbes are critical for plant growth and biogeochemical cycles and are closely related to cultivated crop,

fertilizer applications, and plant residue input [46]. *Sargassum horneri* extract, alginate, can chelate with major cations of Na^+ , Ca_2^+ , Mg_2^+ , and K^+ to form aggregate with richer nutrients, improve the crumb structure and capillary activity of soil pores, and, finally, boost soil microbial activity [47]. Therefore, seaweed extract supplement can potentially be a strategy of enhancing the amount of nitrogen, phosphorous, and potassium contents in soil. Application of seaweed extract on plant is capable of enhancing nutrient concentrations in the leaves, through implication of growth hormone in the process of nutrients absorption and movements in a plant, thus enhancing the weight of the rice plant. The utilization of seaweed-based extracts has reduced the levels of nitrogen, phosphorus, and potassium fertilizers and also induced the seed germination and growth parameters strongly than chemical fertilizers in rice crop [10]. *Ecklonia maxima* seaweed extract is most effective in neutral pH soil, and it can be used to promote plant growth under low pH and water stress conditions [47]. Application of algae mixture of *Corallina elongate*, *Laurencia obtusa*, and *Jania rubens* caused increase in phosphorus content and nitrogen content in maize plant [39]. Decomposed seaweed, as an organic matter, generally improved soil physico-chemical properties, water holding capacity, and microbial activity and also protected plant against unfavorable environmental conditions such as extreme temperatures and water stress [48].

Application of seaweed concentrate led to significantly increase of K, Mg, and Ca concentrations in the leaves of lettuce plants which received adequate supply of nutrients but had meager effect on nutrients-stressed plants. Moreover, the components, nitrogen, phosphorus, and magnesium, were significantly increased when seaweed extract applied through foliar application. Seaweed application in meager quantities has the effect on several metabolic processes and improves plant growth and development through enhancing of photosynthesis, endogenous hormones, nutrients uptake, and protein synthesis as well as with relatively improved ability for increasing available micronutrients in the soil [49]. Foliar applications of *Ascophyllum nodosum* seaweed extract reinvigorated the plants to utilize with soil mineral N and other available nutrients more efficiently which enhanced increased grain potassium uptake and increased in wheat plant yields by 25 percent [50]. Due to increased membrane permeability of roots, leaves, and stoma cells, as well as hormone-like activities of seaweed extract through their involvement in cell respiration, photosynthesis, and enzymatic processes, the application of seaweed extract boosted the uptake of copper. Application of 5 percent of *Kappaphycus alvarezii* sap enhanced the uptake of N, P, K, S, Ca, K, and Mg in leaves of rice crop. Seaweed extract supplement could impact the bacterial community in tillering and heading stages in rice crop, and hence α -diversity of rhizosphere bacteria in the heading stage improved substantially [24]. In the rice environment, enhanced soil available nutrients of N (260 kg/ha), P (42 kg/ha), K (180 kg/ha), Ca (27.7 meq/100g), Mg (5.5 meq/100g), S (18.2 mg/kg), Zn (1.17 ppm), Fe (33.82 ppm), Cu (1.61 ppm), and Mn (18.97 ppm) were observed after applying seaweed extract to the soil at a rate of 25 kg [28]. *Ulva linza* and *Calendula officinalis* contain macronutrients such as N, P, K, Ca, Mg, and some trace elements, as well as growth regulators, amino acids, and antioxidants which are excellent natural fertilizers [51].

Elevation in uptake of K, Ca, Mg, and Cu with application of seaweed extract of *Kappaphycus alvarizii* was due to enhanced membrane permeability of roots, leaves and stoma cells, and hormone-like activities of seaweed extract through their implication in cell respiration, photosynthesis, and enzymatic reactions [27]. Application of seaweed at the rate of 15 percent *Kappaphycus alvarezii* in black gram in sandy loam soil of the red and lateritic belt of West Bengal resulted in higher availability and absorption of inorganic elements like Ca, Na, K, Mg, N, Zn, and Cu [52].

8. Conclusion

Abiotic stress such as drought, high soil salinity, and temperature affect and limit crop productivity worldwide. Biostimulant seaweed application reduces the need for fertilizers and enhances nutritive efficiency, abiotic stress tolerance, grain yield, and plant quality traits. Application of minimal concentration of seaweed extract as a priming agent enhances plant growth, physiological attributes, and molecular traits. Application of seaweed extracts of *Kappaphycus alvarezii*, *Ascophyllum nodosum*, *Sargassum calophyllum*, *Sargassum aquifolium*, *Sargassum polycistum*, *Hydroclathrus clathratus*, *Turbinaria ornata*, and *Turbinaria murayana* are able to stimulate vegetative growth and increase yield of rice plants. The use of seaweed biostimulants in low quantities has effect on several metabolic processes and improves plant growth and development through the increase of photosynthesis, endogenous hormones, nutrients uptake, and protein synthesis as well as with relatively higher capacity for increasing available micronutrients in the soil. In order to boost crop growth parameters like plant height, leaf area index, dry matter production, and SPAD reading (chlorophyll content), as well as yield parameters like the number of grains per panicle, panicle length, and number of products, seaweed extract *Kappaphycus alvarezii* was applied to rice crop (*Oryza sativa* L.) at a rate of 12.5 kg/ha in the soil and 0.5% twice at the tillering and panicle initiation stages. The rice yield was also increased by 18–20% over the recommended fertilizer dosage. However, the application of seaweed extract in soil at the rate of 25 kg/ha improved the available nutrients like N, P, K, Ca, Mg, and S and micronutrients. Hence, seaweed has a substantially greater potential to boost bioavailable macro- and micronutrients to the rice crop.

Conflict of interest

The authors declare no conflict of interest.

Author details

Melekote Nagabhushan Arun^{1*}, Rapolu Mahender Kumar¹, Sailaja Nori², Banugu Sreedevi¹, Guntupalli Padmavathi³, Pallakonda Revathi⁴, Neha Pathak⁵, Dayyala Srinivas¹ and Raman Meenakshi Sundaram⁶

1 Department of Agronomy, Indian Council of Agricultural Research - Indian Institute of Rice Research, Hyderabad, Telangana, India

2 Sea6 Energy Private Limited, Bangalore, Karnataka, India

3 Department of Plant Breeding, Indian Council of Agricultural Research - Indian Institute of Rice Research, Hyderabad, Telangana, India


4 Department of Agronomy, PJTSU, Hyderabad, Telangana, India

5 Department of Botany, Aligarh Muslim University, Aligarh, Uttar Pradesh, India

6 Department of Biotechnology, Indian Council of Agricultural Research - Indian Institute of Rice Research, Hyderabad, Telangana, India

*Address all correspondence to: arun_tulasi2011@yahoo.in

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Seaweed *Kappaphycus alvarezii* Cultivation for Seagrass Ecosystem Conservation

Rajuddin Syamsuddin

Abstract

The physical characteristics of the seagrass ecosystem indicate that the shallow sea waters are ideal for seaweed cultivation. The rapid development of *Kappaphycus alvarezii* seaweed cultivation in coastal areas of Indonesia should not cause damage to the seagrass ecosystem. The study on the cultivation method of *K. alvarezii* seaweed in three seagrass ecosystems in Indonesia showed high growth rates, biomass production and carrageenan content due to high nutrient concentrations and high water clarity as well as the current optimal conditions in the cultivation environment. *K. alvarezii* cultivated in seagrass ecosystems prevents the damaging effects of UV-B radiation on those ecosystems. The right cultivation method applied is the off-bottom method.

Keywords: biomass, carrageenan, growth rate, light intensity, *Kappaphycus alvarezii*, nutrients, seagrass, seaweed sustainability, UV-B radiation

1. Introduction

As many as 25,742 hectares of seagrass spread out in the coastal areas of Indonesia. The seagrass ecosystem is one of the most productive (high organic productivity) marine ecosystems and with high biodiversity. It is supporting fishery production, namely as feeding ground, spawning ground, nursery ground, as well as shelter from various predators and from the hot sun for various fish species.

Seagrass ecosystem are flowering plant (Angiospermae) vegetation that are formed by one or more species with high or rare density that are able to fully adapt in high salinity waters, which cover a coastal shallow marine zone. These physical characteristics of the seagrass ecosystem seems to be the ideal location for seaweed cultivation.

Seaweed cultivation and business in Indonesia are experiencing rapid development and plays an important role in improving people's welfare. However, seaweed cultivation in coastal areas should be carried out in an environmentally friendly manner, without damaging the seagrass ecosystem. *K. alvarezii* is a species of red seaweed (Rhodophyceae) which changed its name from *Euचेuma cottonii* to *Kappaphycus alvarezii* on the basis of the kappa-carrageenan it contains [1], is one of economically important red (macro) algae species that has a high demand on the world market.

Based on the above considerations, a series of studies were conducted in the period 2011–2020 to find the right *K. alvarezii* cultivation method in the seagrass ecosystem that shows high growth rates, biomass production, and carrageenan content, and evaluates its impact on the condition of the seagrass ecosystem. The research was conducted in three seagrass ecosystems in coastal areas of Indonesia, namely in the coastal waters of Tanakeke, Mappakasunggu District, and the coastal waters of Laikang Bay, Mangarabombang District, both are administrative areas of Takalar Regency, South Sulawesi Province. The water depths of both waters of the research location were 500 cm and 250 m, respectively, during high tide. Both have the same current pattern with current velocities ranging from 4.0–8.5 m/second outside the seagrass ecosystem. Another location is the grass ecosystem in Karampuang Island, Mamuju Regency, West Sulawesi Province with a depth of 400 cm during high tide. These three seagrass ecosystems are in one waters, namely the Makassar Strait.

The cultivation method tested in the seagrass area in Takalar Regency was a longline system with three methods, namely the *floating surface longline method*, the *off bottom method*, and the *bottom method*. The *floating method* was placed 20 cm below the sea level, the *off-bottom method* was placed 50 cm above the bottom sediment of the seagrass ecosystem, and the *bottom method* was placed right on the surface of the bottom sediments. While the method used in Mamuju Regency was only the *floating surface longline method*. Seaweed seeds of *K. alvarezii* as much as 100 g/bundle were tied to nylon ropes with a distance of 50 cm between ties and between ropes. Cultivation time was 42–45 days.

Seaweed growth was expressed as daily growth rate and calculated according to the formula suggested by Fortes [2]; Dawes *et al.* [3]; Mtolera *et al.* [4]; Hurtado *et al.* [5]; Munoz *et al.* [6]; Hayashi *et al.* [7]. Some water quality parameters were measured at the research site, including: light intensity falling on the sea surface using a Lux-meter, salinity using a handrefractometer, temperature using a thermometer, pH using a pH meter, current velocity with a current meter, and free CO₂ with titration method [8]. Other chemical parameters were analyzed at the Water Quality Laboratory, Department of Fisheries, Faculty of Marine and Fishery Sciences, Hasanuddin University, Makassar, Indonesia, consisting of nitrate using the sulfuric acid method [9], ammonium and orthophosphate measured using a spectrophotometer [8]. Carrageenan levels were analyzed by extraction of dried seaweed with 0.5% KOH solution at a temperature of 90–95°C.

2. Seaweed growth

Seagrasses absorb nutrients directly from the water column through their leaves and in sediments by their roots [10], their sediments store a lot of accumulated organic matter, 60–80% of which is found in the roots (rhizomes) of seagrass plants, the rest is in the form of stem and leaf fragments of the plants, tissues fragment of aquatic animals, and others. Therefore, the sediment of the seagrass ecosystem is a good habitat for decomposing bacteria. Through the bacteria and various benthic organisms activities, the organic matter are decomposed and releases carbon, nitrogen, and phosphorus and other mineral nutrients. The carbon production of seagrass ecosystems is quite high, ranging from 900 to 4650 gC/m²/year [11] which is a source of high concentration of dissolved free CO₂.

As a submerged soil, ammonium (NH₄⁺) is the main product of mineralization (decomposition) of nitrogen-containing organic compounds in sedimentary soils of

seagrass ecosystems [12]. Ammonium is the dominant form of nitrogen in seagrass ecosystems [13, 14]. Some of the NH_4^+ is oxidized by *Nitrosomonas* bacteria to nitrite (NO_2^-) in the initial phase of the Nitrification process, and the next phase is the oxidation of NO_2^- by *Nitrobacter* to NO_3^- . In addition, under aerobic conditions at the bottom of the seagrass ecosystem that occur periodically at low tide, some ammonium is oxidized to nitrate, so that nitrate is also a form of nitrogen that is also quite abundant in seagrass ecosystems, and is also absorbed by seaweed. Therefore, as a source of nutrients, the sediment continuously supplies carbon, ammonium and nitrate to the above water layer through the processes of turbulence and diffusion. Aerobic bacteria that works around the roots of seagrass plants convert phosphorus that is in a complex state (bound with Fe ions so that it cannot be absorbed by seaweed) into dissolved phosphorus which can be absorbed by seaweed [15].

In the seagrass ecosystem in Takalar Regency, the concentrations of free carbon dioxide, orthophosphate, nitrate, and ammonium ranged from 6.40–6792 ppm, 0.064–0.599 ppm, 0.015–0.65 ppm and 0.047–0.704 ppm, respectively down water column (at all cultivation methods). This value is suitable for seaweed cultivation. The N and P content in seagrass sediments with fine soil particles is higher compared to environments with sandy sediments [16] outside the seagrass ecosystem [15]. These nutrients are stored in high concentrations in sedimentary clay particles of seagrass ecosystems [17], then released into the water column for further absorption by *K. alvarezii* [18].

Nitrogen is an important nutrient in the process of cell division, for seaweed growth, but is most often reported limiting the growth of seaweed [19, 20]. Ammonium (NH_4), which is a form of nitrogen ion (N) with a higher concentration than the concentration of nitrate (NO_3), allows high growth rates of seaweed that was cultivated in seagrass ecosystems. The absorption rate of ammonium by seaweed is higher than that of nitrate [21], because ammonium is a form of nitrogen that enters the metabolic process. Nitrate is reduced to ammonium before combining into organic compounds [22]. Several previous studies have shown that ammonium is a form of N that is directly utilized by plants in protein biosynthesis. In plant cells, nitrate is reduced by the nitrate reductase enzyme to ammonium, the form of N which then combines with organic compounds in the stimulates vegetative growth (thallus) [23].

As a constituent of protoplasm, phosphorus plays a role in reducing plant abortion (stopping organ growth), plays a role in the formation of meristem tissue (tissue consisting of actively dividing cells), stimulates cell division and repairs damaged tissue [24]. This chemical is found in high concentrations in the water column of seagrass ecosystems.

The growth rate of seaweed in the floating method was 1.13–1.53%/day, lower than the off-bottom method (1.34–1.72%/day) on seagrass in the coastal waters of Laikang Bay. The low growth of seaweed using the floating method is probably due to the high exposure to UV-B radiation in the surface water layer. In the surface water layer, photosynthetic pigments (chlorophyll a and carotenoids) are damaged by excessive light intensity and by the damaging effect of ultraviolet UV-B radiation, known as photoinhibition, photodamage (damage by light) and photooxidation (oxidation by light) [25]. Light intensity measured at the water surface in the two seagrass ecosystems ranged from 3700 to 4100 Lux, exceeding the light intensity of 600 Lux for the maximum growth rate of seaweed. The optimal light intensity for seaweed growth ranged from 333 to 1000 Lux [26]. This low level is also caused by the *Warburg Effect* phenomenon due to aerobic (oxic) conditions, which is a very high concentration of dissolved oxygen in water beyond the optimal concentration

due to the diffusion of oxygen from the atmosphere to the water column in the surface layer combined with dissolved oxygen produced during the photosynthesis of the seaweed itself that was cultivated with floating method. The Warburg effect is the phenomenon of competition between carbon dioxide and oxygen on the reactive site of RUBP carboxylase (an enzyme that binds carbon dioxide gas in the dark reaction of photosynthesis), causing only a small amount of free carbon dioxide to be reduced to carbohydrates by the enzyme in the pentose phosphate pathway of the dark (reaction) phase of photosynthesis [24, 27].

With the same off-bottom method, *K. alvarezii* cultivated in the seagrass ecosystem of Laikang Bay showed a lower growth rate (1.34–1.72%/day) compared to 2.20–2.54%/day those cultivated in the Tanakeke seagrass ecosystem. With the same cultivation method, the quantity of sunlight (the same range of 3700–4100 Lux the light intensity falling on the water surface of both waters) which is dispersed, attenuated, and reflected as light travels through the water column at low depths (200 cm in Laikang Bay Seagrass) just a little so that the intensity of sunlight that penetrates the column and exposes the thallus of seaweed is still quite high. Seaweed growth at lower water depths of the seagrass ecosystem, Laikang Bay may be caused by light intensity that exceeds 1000 Lux [28]. While the light hitting the thallus which is positioned at a greater depth (in Tanakeke seagrass ecosystem) the intensity has been greatly reduced (become lower and at least approximately in optimal range) by dispersion, attenuation, and reflection.

The difference in current velocity in these two locations also causes differences in the growth rate of seaweed in these two locations. The current velocity at the bottom of the seagrass ecosystem in Tanakeke is relatively faster (54–56, cm/second) which has an impact on better nutrient absorption by seaweed compared to nutrient absorption of seaweed in the Laikang seagrass ecosystem with a slower current velocity (20–40 cm/sec). The relatively faster current speed causes nutrient uptake relatively more efficient due to the thinner *boundary layer* (the space or layer between the water carrying nutrients with the seaweed thallus). However, current velocities of 20–40 cm/sec and 54–56, cm/second are considered optimal for nutrient absorption. With this method, photosynthesis and absorption of nutrients (CO₂, NH₄, NO₃ and PO₄), both via passive ion absorption through osmosis and diffusion processes and active absorption take place effectively. In addition, seaweed is also physiologically protected from the Warburg Effect at 450 cm water depth.

The low growth rate (1.01–1.27%/day) of seaweed using the bottom method in Takalar Regency can be caused by bacterial activity that breaks down the seaweed thallus which is in direct contact with the bottom of the waters.

High growth of *K. alvarezii* (2.26–2.42%) was only obtained in Mamuju District at the age of 30 days after growth. Beyond the 30th to 45th day of cultivation, there was a decrease in growth which was only 0.28–0.56%/day on the 45th day due to frequent rains at the cultivation location which caused the condition (range) of water quality parameters no longer optimal. The decrease in transparency (high water turbidity) and salinity, as well as the presence of pollutants in the form of waste from residential areas carried by surface run-off by rainfall events are the main causes of the low growth of seaweed. In addition, the influence of river flow that empties into the coastal waters of the cultivation site is the main factor causing the low growth rate of *K. alvarezii*. These factors were also thought to cause some seaweed thallus to be susceptible to a seaweed disease known as ice-ice which causes seaweed death.

The main cause of ice-ice disease is the condition of extreme abiotic factors that exceed the tolerance limit of seaweed [29] such as exposure to very high light intensity, low water salinity, and nutritional deficiencies that cause seaweed to become susceptible to bacterial infections including *Pseudomonas*, viruses and fungi. The initial symptom of this pathogen is in the form of white spots on the thallus, then it changes color to pale, the texture is easily crushed, rots and finally the thallus falls out of the clump.

3. Biomass production

In the seagrass ecosystem in Takalar Regency, the highest seaweed biomass production (18.2–30.83 g/clump) was obtained with the off-bottom method, in line with the growth rate which was also the highest at that particular method, and low in the bottom method (12.4–18.52 g/clump). Nitrogen available in high concentrations in seagrass ecosystems causes high biomass production of *K. alvarezii* cultivated in seagrass ecosystems. This nutrient determines the productivity of algae [14], is very important in the synthesis of chlorophyll a [30] which plays an important role in the photosynthesis process that produces biomass.

4. Carrageenan content

In the process of decomposing organic matter at the bottom of the water, bacteria utilize O₂ and release CO₂ into the water column which is then absorbed by seaweed in the process of photosynthesis which produces carbohydrates, followed by a secondary product in the form of carrageenan. Carrageenan (phycocolloid) is a natural additive that is widely used in various industries, especially the food, pharmaceutical and cosmetic industries. *K. alvarezii* seaweed cultivated in seagrass ecosystems in Takalar Regency produced a fairly high content of carrageenan (39.9–44.8%) in the seagrass ecosystem of Laikang waters, and higher (40.73–50.16%) those grown in the Tanakeke seagrass ecosystem. The carrageenan content is in line with the growth rate because the factors that affect growth are also factors that affect the carrageenan content. Several previous studies [31, 32], also showed that the carrageenan content of *K. alvarezii* was positively correlated with its growth rate. Those that grown in Mamuju Regency also have high levels of carrageenan ranging from 44.95–49.15%, although with a lower growth rate when compared to those that grow in Takalar Regency. These levels of carrageenan exceeds the quality standard set by FAO for industrial raw materials, which is 40%. The carrageenan content of *K. alvarezii* was relatively higher compared to the carrageenan content of 40.7% recorded by Munoz *et al.*, [6], 31.2–38.1% by Hurtado *et al.*, [33], and 30.57–36.93% by Syahrul *et al.*, [34] all of which were cultivated outside the seagrass ecosystem.

Variations in carrageenan content are influenced by several factors, including cultivation location and climate [35]. The high content of carrageenan *K. alvarezii* cultivated in seagrass ecosystems is caused by the concentration of dissolved ammonium in seagrass ecosystem waters [13, 14]. Luning [36] suggested that nutrients (including nitrogen) in sufficient quantities can increase the synthesis of polysaccharides (carrageenan).

Since ammonium instead of nitrate is a form of nitrogen that is directly utilized in protein (amino acid) biosynthesis in plant cells, the abundant availability of

ammonium in the seagrass ecosystem limits the energy (NADPH) that will be used in reducing nitrate to ammonium in protein biosynthesis in algal cells and more energy is used to reduce carbon dioxide in the synthesis of organic compounds (including carrageenan) in the dark reactions of photosynthesis [37] *K. alvarezii*. According to Sahoo and Ohno [19], the concentration of ammonium absorbed by seaweed causes high levels of carrageenan in seaweed.

5. Water temperature, pH and salinity

In addition to nutrients in the form of nitrate, ammonium and orthophosphate, seaweed growth is also influenced by environmental conditions such as salinity, temperature, and sunlight [38]. Water temperature, pH and salinity are environmental factors that affect the metabolism, growth and production of seaweed. Temperature affects the metabolic rate (photosynthesis and respiration) of algae [36, 39]. The temperature of the seagrass ecosystem in Takalar Regency in all vertical water layers is around 29–30°C. Meanwhile in Mamuju Regency the temperature ranged from 29.7–32°C respectively. In general, the temperature required for seaweed growth ranges from 20 to 30°C [36]. *K. alvarezii* can grow at a temperature of 25–29°C [40]. In the tropics the growth rate and biomass production of *K. alvarezii* is high in the temperature range of 25–30°C [41].

pH is a chemical factor that determines the availability of nutrients to be absorbed by plants so that it affects the growth of the seaweed. The range of water pH measured in seagrass ecosystems in Laikang, Tanake, and Mamuju Bays was 7.5–7.8, 7.2–8.0, and 7.5–8.4. The pH range indicates that the three seagrass ecosystems are classified as waters with high productivity. This pH range is optimal for the growth and development of *K. alvarezii* based on Trono's [42] statement that seaweed can live in a pH range of 7.5–8.4. In this pH range, the decomposition of organic matter that accumulates at the bottom of the seagrass ecosystem takes place more quickly, and immediately releases various nutrients needed by seaweed. HPO_4^{3-} is the predominant P ion that is absorbed at pH over 8.

The salinity of the seagrass ecosystem in Takalar Regency in all vertical water layers is 30–31 ppt. Meanwhile in Mamuju Regency the salinity ranged from 29.7–32 ppt. This salinity range is suitable for the growth of *K. alvarezii* seaweed in the tropics. The salinity range of 18–35 ppt is suitable for seaweed growth [6], and very good in the range of 22–30 ppt [43]. Good salinity range for the growth of *Eucheuma* sp. is 30–35 ppt [44]. Doty [45] stated that the desired salinity of *K. alvarezii* ranged from 29 to 34 ppt. Sulu *et al.* [40] stated that 30 ppt salinity was best for the growth of *K. alvarezii*.

6. *Kappaphcus alvarezii* cultivation and sustainability of seaweed ecosystems

Based on the above facts (data from studies conducted in seagrass meadows in Takalar and Mamuju districts as well as supporting academic references), *K. alvarezii* seaweed can grow well side by side with seagrass vegetation, even with high carrageenan content, without having to cut down the seagrass vegetation. There is no competition in meeting nutrient needs between the two because seagrass plants absorb more nutrients from sediment, while seaweed only takes nutrients that are

soluble in water. Even, seagrass vegetation supports the growth of seaweed through nutrient cycles from the sediment to the water layer where the seaweed grows [15]. These nutrients are released into the water column after the decomposition of the leaves and other parts of the seagrass.

With stem and leaf morphology resembling the stems and leaves of land grass and reed plants, as well as their root system that propagates in and on the surface of the bottom sediment, seagrass acts as a sediment trap and stabilizes the bottom sediment [46], so it is not easily stirred by the movement of water (current and waves), dampening the waves and currents that cause the water mass to become calm and clear (high transparency) in this ecosystem. This ecosystem has the characteristics of low current velocity, as a storehouse of mineral nutrients which are recycled from the sediment to the water column above it. This condition is really needed by seaweed for its growth and development. Therefore, high daily growth rate, biomass production and carrageenan content of *K. alvarezii* were obtained using off-bottom cultivation method in seagrass ecosystems. With the availability of natural food in the form of leaves of seagrass plants, epiphytic algae and animals attached to the sediment substrate, leaves, stems and roots of seagrass, the attack of herbivorous fish on seaweed can be reduced.

Until now, there is no indication of any negative impact of seaweed cultivation on seagrass growth, especially for *Enhalus acoroides* seagrass. Most seagrass species can survive in low light intensity by means of physiological as well as morphological, or the anatomical structure adaptations of the leaves [47]. Growth is mainly influenced by water quality parameters. During the cultivation of seaweed in these three seagrass ecosystems, the seaweed farmers' activities did not cause physical damage to the seagrass plants. Seagrass degradation is most likely to occur if the plant is trampled by the cultivator. However, when doing seaweed cultivation activities in the seagrass ecosystem, this does not happen because the series of activities ranging from attaching ropes to harvesting are all carried out by boat without stepping on seagrass plants at the bottom of the waters.

The seagrass meadows have high biodiversity and are one of the marine ecosystems with high organic productivity, which supports food chains and food webs in the sea, both based on herbivorous and detritivorous chains. Through the decomposition process of detritus and other organic matter, these waters are a natural food habitat for benthic animals and filter feeder invertebrates that consume detritus particles. With soft bottom sediments, seagrass ecosystems become niches for various benthic animals (zoobenthos), including polychaeta, crustaceans (shrimp, prawns, crabs), sea urchins, mollusks, and sea cucumbers. Important economic fish species that are often found foraging in this ecosystem include rabbit fish (*Siganus canaliculatus*, *S. fuscescens*, *S. guttatus*), *Mugil* spp., grouper, *Epinephelus* spp., *Neoniphon sammara*, *Scarus* sp., *Lethrinus harak*, *L. orantus*, *Lutjanus kasmira*, *Pomacantus semicirculatus*, *Calatus spinidens*, and *Parupenous berberinus*. Some of these fish are either as a seasonal resident, visitors, or occasional residents in this ecosystem. Other marine organisms are sea horses (*Hippocampus* spp), turtles, and dugongs.

As a shallow marine ecosystem, seagrass ecosystems are very sensitive to the adverse effects of ultraviolet radiation, especially UV-B (wavelength 280–320 nm) which exposes and penetrates down the water column of seagrass ecosystem. With thin leaf anatomy, seagrass plants are sensitive to UV radiation, so that in the future, this radiation will have a negative impact on the sustainability of this ecosystem [48].

K. alvarezii, a species of red algae (Rhodophyta) known as a group of algae with high red, orange and yellow pigments in its tissues. These pigments are carotenoids

and their derivatives, such as lutein, loroxanthin and siphonaxanthin content. Carotenoids are generally found in cell membrane systems where one of the main functions of these compounds is related to photosynthesis. The carotenoid content of *K. alvarezii* that we recorded in our study on the cultivation of this species in two districts of Takalar Regency was 0.02–0.03% in the dry season when light intensity was high enough, and 0.06–0.17% in the rainy season where relatively lower light intensity. This explains that the carotenoid synthesis is high under conditions of low light intensity, and low under high light intensity. Carotenoids are accessory pigments that function to capture sunlight energy at certain wavelengths beyond the wavelengths that can be captured by chlorophyll and other photosynthetic pigments [49]. The formed carotenoids then act as protecting compounds against the destruction effect of ultraviolet UV-B radiation on the seagrass plants, known as photoinhibition, photooxydation and photodamage [50–52]. Through cultivation in an environment with high nutrient concentrations, the carotenoid content of *K. alvarezii* cultivated in seagrass ecosystems is also high.

As a macroalgae, *K. alvarezii* contains mycosporine-like amino acid compounds (MAA), the compound that gives seaweed species the ability to tolerate the effects of UV-B radiation. Under certain conditions, through the pigmentation mechanism in which the synthesis of carotenoid pigments increases, and with a thick thallus, with a multicellular layer, as well as morphological adaptations where the *K. alvarezii* clumps become denser when there is an increase in light intensity, cultivating this algae species in the seagrass ecosystem provides shade for seagrass from the UV-B radiation, and can physiologically reduce or inhibit the negative effects of the radiation on seagrass plant tissues. Thus, through the off-bottom method of seaweed in this seagrass ecosystem, it is possible to minimize the destructive impact of UV-B radiation before exposing seagrass plants, and recover the damage from the effects of UV-B radiation. Thus, this cultivation can maintain the sustainability of the seagrass ecosystem as a provider of ecological and socioeconomic services.

7. Conclusions


Based on the discussion, it can be concluded that *K. alvarezii* seaweed can grow well with high carrageenan content in the seagrass ecosystem, without having to clear seagrass plants. By cultivating seaweed in the seagrass ecosystem, the seagrass vegetation is protected by the seaweed clumps from the negative effects of ultraviolet radiation which can damage the seagrass vegetation in the long term. With the off-bottom cultivation method and 100 grams the initial weight of the seedling with a tie spacing of 50 cm, the cultivation of *K. alvarezii* in the seagrass ecosystem did not inhibit the growth and development of seagrass vegetation.

Author details

Rajuddin Syamsuddin
Faculty of Marine Science and Fisheries, Fisheries Department, Hasanuddin
University, Makassar, Indonesia

*Address all correspondence to: rajuddin_syamsuddin@yahoo.com

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Chapter 4

Marine Bivalves' Ecological Roles and Humans-Environmental Interactions to Achieve Sustainable Aquatic Ecosystems

Andreia Filipa Mesquita, Fernando José Mendes Gonçalves and Ana Marta Mendes Gonçalves

Abstract

Bivalve species have a key role at the ecosystem level and a very interesting economic value. Globally, bivalve production is higher than 15 million tons. Thus, this work intends to highlight the economic value of these organisms, but mostly highlights the potential of this resource for water management and water quality improvement, and thus to the sustainability of aquatic systems, which gives them a particular interest. These organisms are under anthropogenic pressures becoming crucial to preserve aquatic systems and their communities, namely bivalve communities, and water quality by reducing pollution. UN Sustainable Development Goals (SDGs) highlight the main actions to reduce humans' footprint and to create globally a model to guarantee human security, to protect the environment and water quality and to combat climate changes. To achieve the UN SDGs, bivalves may have a high importance for sustainability and preservation of freshwater and marine systems (SDG 14), and for water management (SDG 6), due to their ability to improve the water quality by reduction of pollution. This work aims to highlight the main ecological roles of marine bivalves and the human actions that will contribute to achieve sustainable aquatic systems, and so the SDG 6 and SDG 14 by 2030.

Keywords: bivalves, food resources, water quality and management, sustainability, ecological roles

1. Introduction

Water is a valuable resource to human beings; however nowadays, 2.2 billion people continue without access to safe drinking water [1].

Freshwater ecosystems provide us several services, such as transport, natural purification, protection against floods, irrigation, and they are characterized by a high biodiversity of habitats. Unfortunately, the discrepancy between developing and developed countries is considerable. In developed countries, 3.5% of the land is

covered by freshwater, compared to just 1.4% in developing countries [1]. Despite the importance of freshwater, this only includes less than 3% of all water in the world. By other side, oceans comprise about 97% of all water in the planet [2] and have an important ecological role, as habitat to many animal and plant species, of all sizes, being essential efforts to the conservation and preservation of these systems. In addition to the ecological importance, these ecosystems have a great value to the human development, since they provide many resources, including economic activities as fishing, communications, tourism, and recreation activities. Marine vegetation is responsible for the production of about 50% of atmospheric oxygen; mangroves, saltmarshes, and seagrasses have a key role as natural sinks of carbon; coastal habitats present high importance to the protection of habitats, communities and businesses against storm, and wave damage; and humans ascribe great esthetic, cultural and spiritual values from ocean ecosystems [3]. So, due to the great potential of these ecosystems, human populations have developed their activities and inhabited near the sea, with 67% of human population living less than 400 km from the sea [4].

Notwithstanding the great value of the aquatic systems to many species and to human well-being, these environments have been neglected and subjected to many pressures, such as resource overexploitation (e.g., overfishing) and input of pollutants from human activities (e.g., industrial and agricultural practices, shipping, beach activities). Therefore, these pressures result in dangerous effects to the entire ecosystems, including consequences to the biotic (e.g., changes in the structure and function of the communities) and to the abiotic (e.g., effects on water quality and sediment composition) elements. Considering the importance of each species and the ecosystem as a whole, it is essential to work for the preservation and conservation of these ecosystems, reducing the impacts of anthropogenic activities and improving water quality. So this work attempts to highlight the human role in the sustainable management of freshwater and marine aquatic systems, focusing on bivalve communities, due to their ecological and economic importance.

2. SDG 6 and SDG 14

Sustainable Development Goal 6 intends to achieve an equitable access to drinking water and sanitation for all people, through several targets. It includes the elimination or reduction of the pollutant inputs to aquatic systems, encouragement of the cooperation between countries for the implementation of integrated water resource management, and assurance of the protection and recovery of water related ecosystems (e.g., wetlands, lakes, and rivers). SDG 14 is focused on marine ecosystems' preservation and conservation. This is achieved through measures to prevent and reduce marine pollution, including land activities, to minimize ocean acidification and its consequences (e.g., decreased carbonate ions' interference with shell formation, affecting the survival of bivalves, plankton, and coral reefs) and by promoting the sustainable use of marine resources through economic benefit assessment.

Considering these two SDGs and their targets, it is crucial human beings and different sectors take actions to achieve the 2030 Agenda main goals. Several efforts are essential, such as effective policies to control the impact on aquatic systems, both from contaminant discharges and from resource overexploitation. Moreover, spreading the knowledge of environmental issues and involving people in environmental activities may also be fundamental to the awareness of the non-scientific communities, making easier the implementation of policies and the achievement of the goals. Ocean Literacy

and Environmental Education programs for school students and the public in general may contribute to promote knowledge, awareness, and governmental action.

The critical position of bivalve species in the ecosystems, acting as a link between primary producers and secondary consumers, and their ability in filtering and cleaning the water and in accumulating great amounts of nutrients and contaminants is well known. Their role in carbon and nutrient cycles is fundamental to achieve clean water and ecosystem health. Thus, a compilation of bivalves' importance and the role of anthropogenic impacts on aquatic systems, for achieving SDGs 6 and 14 are provided in the section below.

3. Ecological and economical role of bivalves species

Bivalves (Bivalvia) are a large class, with almost 15,000 species (MolluscaBase 2021). These organisms are found worldwide in marine and freshwater ecosystems and they are reported as playing a key role at the ecological level, due to their large filtration ability. These organisms are filter feeders and filter plankton and other suspension particulates, contributing to the water cleaning and light penetration. They also have an essential part in the ecosystem hydrodynamics as well as in nutrient and carbon cycles [5]. Their high filtration ability and potential for use in bioremediation processes [6] make them potential key elements for the improvement and restoration of water quality. Moreover, they are a food source to many species, from invertebrates to fishes, birds, and mammals [7], acting as a link between primary producers and secondary consumers. Briefly, they can establish and change habitats and affect the trophic webs, directly and indirectly [8]. By this, bivalve species preservation is an important contribution to the ecosystem's equilibrium and resource sustainability, being a key element to achieve SDGs 14 and 6.

Despite the great ecological importance of these organisms, bivalve species also have a great economic value to humans, since they are used not only as ornamental objects but also as a food and protein source. For instance, in 2017, 40,000 tons of global oyster were imported, and about 170,000 tons of clams were exported and 180,000 tons imported, with China as the main exporter whereas Japan and Republic of Korea as the main importers [9]. Scallop import prices in the French market were US\$15/kg for frozen scallop and US\$20/kg for live scallop in 2019 [10]. Many species also have an esthetic value, providing ornamental objects such as pearls and decorative shells. Worldwide production of unworked pearls reached US\$412 million and that of worked pearls was US\$ 787 million in 2004 [11], promoting the fishing industry in coastal zones [11, 12]. In Europe, bivalve production in aquaculture systems is reported to be about 598 thousand tons per year, and global production exceeds 15 million tons, translating to about 20.6 billion dollars per year worldwide [13]. Bivalves' application for the human wellness are many, such as the ornamental and food resources, including the extraction of bioactive molecules with medical use, due to its antiviral [14] and antibacterial (e.g., the lectin MytiLec-1 extracted from *Mytilus galloprovincialis* and with the ability to inhibit the growth of Gram-positive and Gram-negative bacteria) [15] properties. They are also able to cause the apoptosis of cancer cells [16–18] and have the potential to the development of novel food products, due to antioxidant extracts from the bivalves shell [19–21]. Considering the important ecological and economic value of these organisms, the growing deterioration of bivalves' communities should also be a major concern to all and thus to the achievement of the goals of Agenda 2030.

4. Anthropogenic pressures

Anthropogenic activities, particularly the industrial and urban development, agricultural practices, tourism, and recreational aquatic activities [22–24] contribute to the aquatic ecosystems' pollution, as well as the exponential increase of the human population. Consequently, the food need leads to organisms' overexploitation. These pressures, pairwise the introduction of alien species, accidental or per esthetic and economic reasons, are leading to the habitats' degradation, affecting the aquatic ecosystems [25, 26] and interact by complex and unpredictable ways, with dangerous consequences to the systems, affecting their stability and resilience [27], resulting in bivalves communities' decline. Several researchers [24, 28–30] have dedicated their studies to understand the effects of environmental contaminants on aquatic ecosystems and consequently on the species.

Despite the pressures resulting directly from human activities, aquatic ecosystems are also very susceptible to climatic changes. Nowadays, global changes comprise a main concern to scientific, political, and social communities. IPCC [31] predicts a temperature increase of the Earth's surface of about 4°C until the end of twenty-first century, with dangerous impacts to the aquatic systems and organisms, being particularly aggravated by bivalves' species [32].

The main reasons and effects of the above-mentioned stressors are detailed in the further subsections, considering its impacts on the aquatic systems and particularly to the bivalves' populations. The selection of stressors was based on its increase and harmful effects, and comprises the: i) chemical contamination (including pharmaceuticals, pesticides, and metals) and microplastics, highly used in daily activities by human beings (e.g., pesticides used worldwide increased 1 million tons in the last 30 years) [33]; ii) overexploitation of resources, resulting from the increasing of the food requirements [34]; and iii) the climatic changes (**Figure 1**) [31, 35].

4.1 Contaminants

Many effects have been reported at the individual level (e.g., inhibition of the growth, reproduction, behavior, and survival) [22, 24, 30, 36], being usually associated with causes at a molecular level, such as changes in detoxication, neurological, immunological, metabolic and antioxidant processes, biomolecules, and DNA [29, 37–47].

4.1.1 Pharmaceuticals

Chemicals designed to act on specific molecular and metabolic pathways of animals and humans, nevertheless, may affect non-target species [29]. These contaminants enter on the aquatic systems mostly by industrial effluents, livestock wastes, human excretions, hospital wastes, and incorrect discarding of pharmaceuticals, incomplete drugs removal of many medicines, by wastewater treatment plants, and release of contaminated effluents and sludge containing drugs [48, 49].

4.1.2 Pesticides

Chemical formulations, mostly from agricultural use for pest control (including insects, weeds, parasites, fungi and rodents) [50], may affect the organisms directly, by their toxic effects, or indirectly, by the elimination of other species [51].

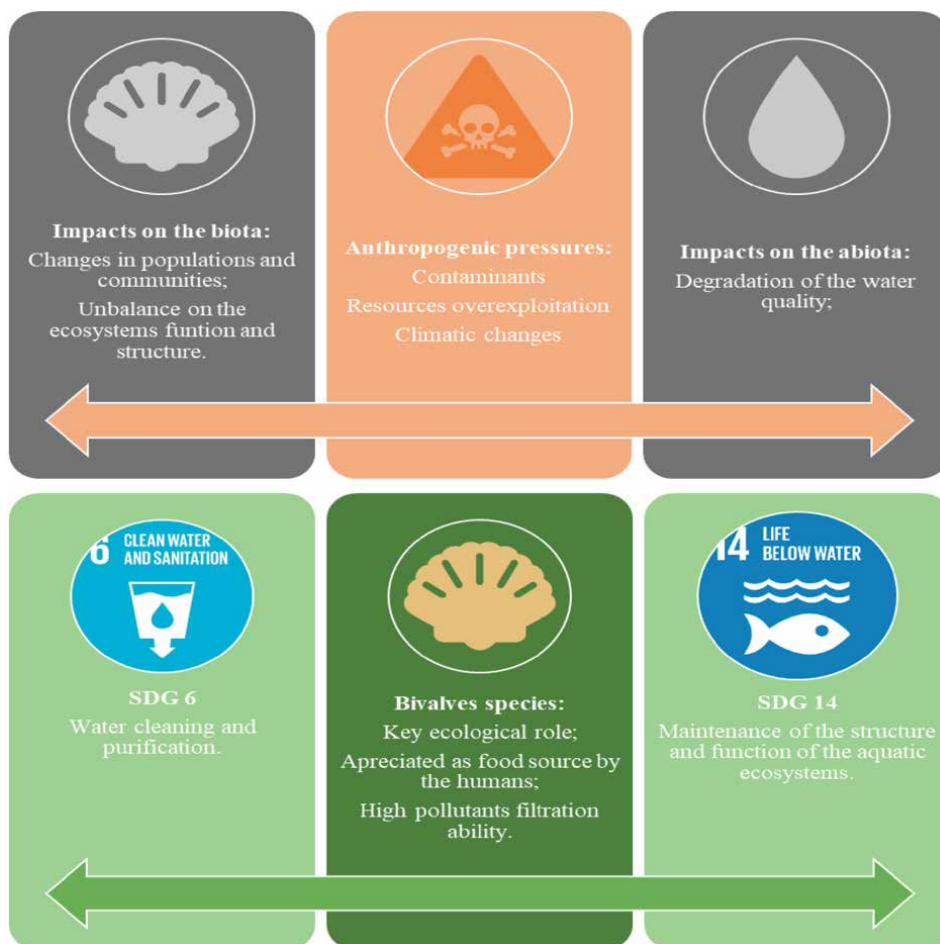


Figure 1.
Bivalves ecological roles and the impacts and pressures of human activities.

4.1.3 Metals

Metals can be from industrial and mining activity, metal plating, rainwater runoff, and sewage [52–54], or released by natural sources [55]. These compounds can be classified into two categories—essential metals and non-essential metals. Essential metals have a biological role in the organisms (e.g., copper, iron, magnesium and zinc) [56, 57], but still they may be toxic at high concentrations. Non-essential metals have no role in organic processes (e.g., mercury, lead, cadmium, and arsenic) [58, 59], being toxic even at very low concentrations [60].

4.1.4 Microplastics

These emerging contaminants are a worldwide concern among political and scientific communities, but also to the general public [61, 62]. These particulates may be from the degradation of bigger plastic elements or plastic initially produced with a little dimension for commercial application [8]. They are easily ingested by organisms

from various trophic levels [63–66] and have the ability to accumulate in bivalves [28], with potential consequences to human health. Fang et al. [67] reported an ingestion of 2565 microplastics items by volunteers, after consumption of 225 g of mussels, an exposure classified as considerable [68, 69]. Moreover, studies estimate an annual ingestion of microplastics per person, as consequence of the shellfish consumption, of about 87 to 11,970 items [70]. The interest in microplastics studies is increasing, and some researchers have observed dangerous effects on bivalves, as a consequence of the exposure to these particles. Browne et al. [71] demonstrated microplastics translocation to hemolymph and to hemocytes. Structural and morphological changes on tissues and effects to the gills and digestive gland were shown by Alnajjar et al. [28]. Other authors also stated reactive oxygen species production, oxidative stress generation, and DNA chain breaks [72, 73].

The above-mentioned contaminants have dangerous effects on bivalves' species and the remaining aquatic communities, and on water quality and consequently on human beings. Considering the 2.2 billion of people without safe access to drinking water and the resources provided by aquatic systems, the preservation of these ecosystems is essential. Some policy measures, such as fines, have been implemented to control contaminant discharges to aquatic systems; however, this problem remains. Therefore, aggravation of fines for those who do not comply, more intensive supervision, and more restrictive laws are necessary to ensure availability and sustainable management of water, and also to achieve a sustainable use of the oceans and the marine resources. Moreover, measures like attribution of economic benefits for the safe disposal of pollutants could be implemented, helping to restore an appropriate water quality. Another measure to reduce pollution is the application of natural fertilizers in agriculture fields, which are healthier for soils, cultivated products (also increasing their quality), human health, and the surrounding aquatic systems [74]. Improved irrigation techniques, like those already used in some countries where water resources availability is a problem, can help to reduce agricultural water use. These are some of the measures to achieve some of the targets of the SDGs 6 and 14 of Agenda 2030.

4.2 Overexploitation of resources

During the past century, the development and usage of resources to improve living standards proceeded rapidly, in some cases without concern for the sustainability of the systems and resources. The management and implementation of mitigating measures in threatened aquatic ecosystems were also conducted to restore ecological health, mainly in those surrounded by agriculture fields with intensive practice. The overexploitation of agriculture fields hastened to a depletion of land resources, which poses a new challenge to develop new food sources focused in marine resources [75]. Contrary to land systems, in the ocean the access to resources outside of national jurisdiction is practically unregulated. Furthermore, in territorial waters and exclusive economic zones, where there is regulation, it is often ineffective. Several consequences are frequently associated with non-regulation, such as overfishing, blocking of maritime shipping ways, coastal habitats destruction, introduction of dangerous alien species, and occasional and pollution above the resource assimilation ability [76].

Some researchers have reported population changes associated with overexploitation, namely the decrease of demographic, temporal, and spatial diversity [77],

changes in population age and size, decrease of genetic diversity, and changes in growth rate and reproduction [78]. Moreover, variations in trophic structure as consequence of overexploitation are reported [79–82], as well as, biomass decline [83].

Among the many methods of overexploitation of resources, many research studies have been focused on fisheries using equipment that damage benthic habitats and pose risks to the administration, balanced use, and preservation of live resources [84–87]. Hand collection of mollusks (mussels, clams and oysters) is among the most susceptible of artisanal fisheries, due to its distribution and economic value in the coastal zones [88–90].

To achieve SDG 14, some measures (e.g., attribution of economic benefits to the sustainable use of marine resources, prohibition of subsidies that contribute to the overfishing, determination of fishing quotes) [91] should be applied to support sustainable fishing that ensures the continuation of the species and protect aquatic communities. However, fishing is the livelihood of many people, who often lack access to basic information, and therefore knowledge-sharing programs highlighting the importance of the ecosystems and resources preservation are badly needed.

4.3 Climatic changes

Nowadays, climatic changes are the main concern among political and scientific communities, with SDG 13 focusing on urgent action to combat climate change and its impacts. It is recognized that climatic changes affect all life forms, and marine ecosystems are not an exception. So several studies have showed the climatic change impacts on these systems [92, 93], namely warming and acidification of the oceans [94], changes in the nutrient dynamics, increase of CO₂ levels, and alterations in wind and flow patterns [95]. Consequently, the survival, growth, reproduction, and distribution of species are affected, and the impacts also may be observed at higher levels such as population, community, and ecosystem [96]. Some studies have linked climatic changes with dangerous biological effects on bivalve species, such as shell formation [94], abundance [97], development [98], larval stage [99], recruitment [100–102], and spawning [103].

Ecosystem monitoring is fundamental to understand the long-term evolution of ecosystems, allowing the detection of changes in biotic and abiotic parameters and intervention to restore ecosystem balance. Some efforts have been done by scientific research groups to monitoring these ecosystems, such as determining and quantification of metals [104–106], organic pollutants [107–109], and microplastics [110, 111]. The ocean acidification impact [112, 113], the development of technology [114], or even creation of marine sanctuaries [115] are other contributions to the monitoring programs. However, these programs are poorly funded by governments and are mainly dependent on the scientific research efforts, being crucial a more effective and higher financial support.

5. Conclusion

Anthropogenic pressures on aquatic systems are increasingly intense and need better understanding of their impacts on ecosystems and communities. This review highlights the dangerous effects of pressures from human activities, with a focus on contaminant inputs, resource overexploitation, and climatic changes. Moreover, this

work intends to be an alert to the importance of aquatic ecosystems' recovery and preservation, and thus water quality, with a focus on the ecological role of bivalve species. This work also calls attention to the decline of these communities and the impacts on the ecosystem structure and functioning, not only in marine systems but also in freshwater environments, where bivalves may have a great potential for water cleaning and purification. Human beings have a key role in the preservation and conservation of aquatic systems, species, and water quality through the application of mitigation measurements and strategies. It is crucial to act to achieve the goals and targets proposed in Agenda 2030 for a better and a more sustainable future. The future depends on us!

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Author contributions

Conceived and designed the idea, A.F.M. and A.M.M.G.; organization of the team, A.M.M.G.; writing and bibliographic research, A.F.M.; supervision and manuscript revision, F.J.M.G. and A.M.M.G. All authors have read and agreed to the published version of the manuscript.

Author details


Andreia Filipa Mesquita¹, Fernando José Mendes Gonçalves¹ and Ana Marta Mendes Gonçalves^{1,2*}

1 Department of Biology and CESAM, University of Aveiro, Aveiro, Portugal

2 University of Coimbra, MARE - Marine and Environmental Sciences Centre / ARNET - Aquatic Research Network, Department of Life Sciences, Calçada Martim de Freitas, Coimbra, Portugal

*Address all correspondence to: amgoncalves@uc.pt

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Non-Indigenous Marine Fish in Syria: Past, Present and Impact on Ecosystem, and Human Health

Adib Saad and Lana Khrema

Abstract

Biological invasions have posed a major threat to global and regional biodiversity. The Mediterranean, one of the world's main biodiversity hotspots, has long suffered from multiple and recurrent invasions. Due to the geographical location of Syria on the eastern Mediterranean coast, this chapter includes a historical and recent study over the past hundred years of the biodiversity reality of fish fauna in Syrian marine waters (as a representative part of the Levantine Basin). It also includes the evolution non-native fish species number that migrated to this area, both from the Red Sea (through the Suez Canal) and from its original habitats in both Indian and Pacific Ocean, or from the Atlantic Ocean through the Strait of Gibraltar. Then, its spread extended to Syrian territorial waters due to the impact of climate change, which led to environmental changes in the characteristics of the marine waters. An explanation will also be given of the impact of non-indigenous species on native species such as competition for food, ecological niches, and predation, as well as the positive and negative effects on the economy and human health. The consumption of some invasive species, like buffer fish rich in tetrodotoxin, may lead to severe intoxication, sometimes to death.

Keywords: alien species, Lessepsian migration, Mediterranean Sea, tropicalization, marine ecosystems, range extension, Syria

1. Introduction

The habitats of the world's seas and oceans are under siege by invasive alien species, leading to adverse and irreversible consequences for native biodiversity, ecosystem services, the economy, and human health. However, there are some positive aspects resulting from the migration of certain species of high economic value (such as certain types of fish, mollusks, and crustaceans), provided that there is no intense environmental and food competition with local species. Climate change, the increase in the number, tonnage and speed of merchant ships, the widening and deepening of artificial channels, the pollution, and the increase in various human activities contribute to the success of the introduction and establishment of these species. The competition on habitats is a major threat to the structure and functioning of critical marine communities, destroys the exploitable areas, or reduces the

productivity of marine environments. In this context, long-term monitoring studies have become necessary to assess the magnitude of these factors and prepare effective management plans to deal with these challenging issues [1]. The Mediterranean, one of the main biodiversity hotspots in the world, has always suffered from multiple and recurrent invasions. The first alien species recorded in the Mediterranean were a pair of fouling serpulid polychaetes, *Hydroids dianthus* Morch, 1863, and *H. diramphus* (Verrill, 1873), collected from the ports of Izmir and Naples in 1865 and 1870, respectively [2, 3]. As the Suez Canal was inaugurated in 1869, we can say that the arrival of these two species in the Mediterranean is due to cargo or transport ships. The next two species were Red Sea mollusks, *Pinctada radiata* (Leach, 1814) and *Cerithium scaridum* Philippi, 1848, collected at Alexandria and Port Said in 1874 and 1883, respectively [4, 5], announcing the Eritrean invasion of the Mediterranean Sea. The influx of alien species has continued since, and evolves with time, human activities, climate change and resulting changes in the physicochemical characteristics of Mediterranean water.

The impacts of alien species have not been undertaken in a serious and deepened way until the beginning of the twenty-first century. The preponderance of species arriving in the Mediterranean *via* the Red Sea (called Eritrean) in the south-east of the Mediterranean, which was called integral Syria (**Figure 1**), or natural Syria [6].

The invasions have been perceived until the beginning of the twenty-first century as singular and widely in the world that bioinvasions constitute one of the most important elements of global changes, with often harmful effects on biodiversity, the economy, and human health.

Many atlases and articles (fish, crustacean and mollusks) summarize existing knowledge of the scale and impact of alien species in the Mediterranean [7, 8]. Research publications, surveys, and conference abstracts indicate that the alien species recorded in the Mediterranean Sea till 2020 more than 188 species of fish are thus

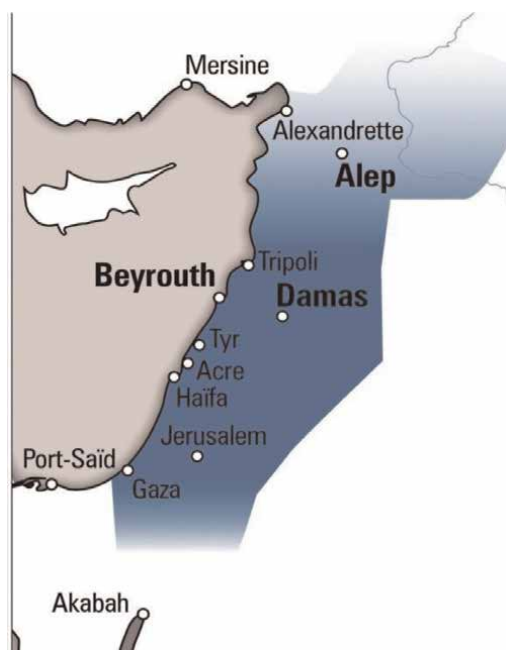


Figure 1. Map of the coast of greater Syria in 1914, this coast that grovel surveyed marine life during 1929–1931.

broken down: 25 introduced by shipping, mariculture and aquarium releases, or by other human activities; 106 species crossed the Suez Canal; 57 Atlantic species whose arrival in the Mediterranean Sea is attributed to unassisted migration through the Strait of Gibraltar [9]. Through our current reference study, we estimate the number of fish species that entered the Mediterranean until the end of 2022 at about 214 species, of which about 120 species entered through the Suez Canal, 65 species of Atlantic species, and 29 species introduced by shipping, aquaculture, or other human activities. We will focus in this chapter on the group of exotic fish invading the territorial waters of (current) Syria, which constitute the extreme east of the Mediterranean coast and a hot spot to receive species introduced into the Mediterranean Sea *via* the Suez Canal. This is attributed to the great Atlantic current from west toward the east (Coriolis Force), bringing with it the larvae, eggs, and adults preferably toward the east and north in front of the east coast, before gradually scattering in the eastern basin, and then throughout the Mediterranean (**Figure 2**).

Figure 2 clarifies that the eastern coast of the Mediterranean, with the Syrian coast in the middle, is primarily subject to the arrival of migratory species from the Red Sea (Lessepsian), due to the main marine current heading from east to west and then to the north in a counterclockwise direction, in addition to the environmental characteristics (temperature and salinity), closer to the characteristics of the waters of the Red Sea than the rest of the Mediterranean.

Syrian sea water occupies about 4000 km² of the Levantine Basin in the eastern part of the Mediterranean, where the Syrian coast extends 183 km from the Turkish border in the north to the Lebanese border in the south (**Figure 3**). The Syrian marine waters as part of the Levantine Basin and the easternmost part of the Mediterranean Sea are characterized by high salinities and high temperature. In the Mediterranean, salinity exhibits an east ward increase, from approximately 37.5‰ in the west to 39.5‰ in the east; temperature increases from west to east, ranging from 15 to 26°C [11]. Gruvel [6] was the first specialist to report on the marine ichthyofauna of the Eastern

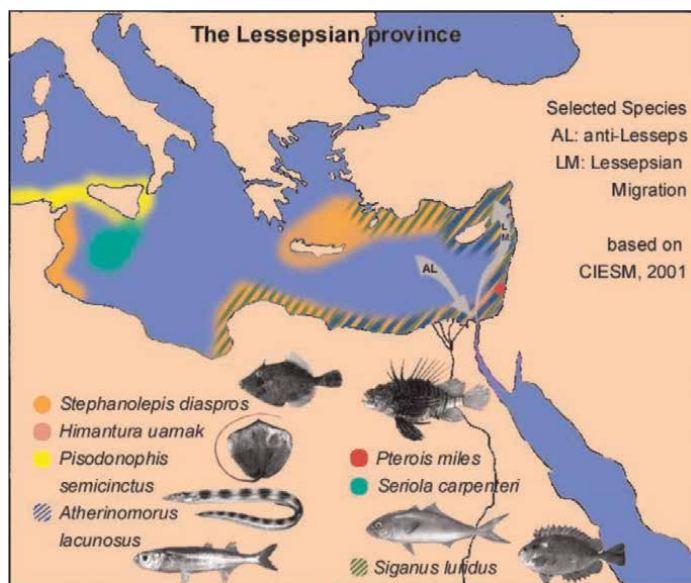


Figure 2.
Species migration from the Red Sea to eastern coast of the Mediterranean.



Figure 3. The exclusive economic zone (EEZ) and shelf area (to 200 m depth) of Syria [10].

Mediterranean Sea. Forty years later, a local study was carried out on the marine ichthyofauna from the Syrian coast [12]. During the last three decades, several studies have been carried out sporadically, and all recorded species have been documented with voucher specimens, photographs, and scientific publications [13–17].

2. Definitions and working methods

An alien species is defined as an organism present outside its known or consensual range [18]. Alien species were grouped into four main categories, namely established, casual, questionable, and cryptogenic, the definition of these terms can be found in Ref. [19]. Clearly and concisely, the established species are the exotic species with self-maintaining populations; casual species are the species which were reported only once in the region; questionable species are the species which were reported without sufficient information and their taxonomic status is uncertain; cryptogenic species are the species with no definite evidence of their native or introduced status according to Carlton [20]. Other important definitions to know are as follows:

Invasive species are the established exotic that have overcome biotic and abiotic barriers in the region and are able to expand their distributional ranges through the production of fertile offspring, with noticeable impact on the prevailing ecosystem.

The Lessepsian migration refers to the migration through the Suez Canal (planned by Ferdinand de Lesseps), generally, from the Red Sea to the Mediterranean, and rarely in an opposite way, favored by two distinct man-made events: the creation of a waterway between the Indo-Pacific and the Mediterranean basins and the control of the Nile fresh-water outflow.

Range expansion refers to species that have recently arrived in a given area by natural dispersal from a neighboring area in which they are native, without the intentional or unintentional intervention of human.

The increase in shipping and the opening of the Suez Canal predates modern studies of Mediterranean marine taxa, saving mollusks and fish, by at least half a century. Since the beginning of the twentieth century, extensive biological studies have been carried out in the Mediterranean, allowing a reasonable measure of confidence in the separation of alien from native biota in the best-known taxa. Since the probability of encountering a stray animal at sea is less and less important, most recorded alien species are considered “established” species that have self-sustaining populations of some duration. It is recognized that some alien species may not maintain their populations over time, and therefore, a single record dating back decades may be considered an ephemeral entry. The distinction between “established” and “ephemeral” extraterritorials can vary in space and time and is sometimes difficult to discern and largely circumscribed by our unfamiliarity with the marine environment. This study is geographically restricted to the Levantine Basin—in general—and specifically the Syrian marine waters. The list of species was taken from several sources. Primary sources include research articles, fish fauna inventories, fisheries management studies and reports, author-supervised, and unpublished M.Sc. and Ph.D. theses conducted over the past 30 years. The dataset includes the native range of the extraterritorial, and its means of introduction, whether through the Suez Canal, ships (drilling hull transport, fouling, crevicultural or clinging species, and ballast), marine cultivation (intentional or not), and other commercial introductions (ornamental, bait, edible species).

The results presented in this chapter depend mainly on the results of field research conducted by the author and his team during the past three decades, represented by the results of master’s and doctoral researches and the author’s research whose results have been published in scientific journals. In addition, the data for this chapter included a review of the results of work published by other researchers in the area. The work included following up the landing of fish in fishing ports, studying the quantitative and qualitative composition of the catch, as well as following up with local fishermen to inform the author of any unfamiliar fish species so that the author or a member of his team could bring the fish sample to the laboratory for study and classification, and then the results in a scientific journal are published. Each reference will be mentioned next to each new result in succession in the results and discussion section.

3. Results and discussion

3.1 List of species and composition of fish fauna

A total of 106 species of exotic fish have been identified in Syrian marine waters until end of August 2023. While the number in 1931 was only seven species [6], in 1976 it rose to 11 species [12], while in 2005 it reached 54 species [15], and since that date the acceleration in recording the presence of exotic species has now reached 106 species out of 343 species (**Tables 1** and **2**). The total number of fish species in Syrian marine waters, that is, about 30% of the total fish fauna in this region, and this large increase in the number of alien species are attributed to the following:

1. climate changes and the subsequent changes in the environmental characteristics of water and the food chain,

Category	Species	Families	Orders	Alien
Chondrichthyes	50	25	10	5
Actinopterygii	292	98	26	101
Class:Hyperoartia	1	1	1	—
Total	343	124	37	106

Table 1.

Number of recorded fish species and lamprey from Syrian Marin water, and number of alien species.

2. the increase in human activities represented by fishing and transportation,
3. the second Suez Canal was built, which increased the migration of more tropical species from the Red Sea to the Mediterranean (**Figure 3**), and
4. increased monitoring and scientific research in the field of biodiversity and ecosystems.

3.2 Coexistence with local species

Alien species composition differs between ecoregions in the Mediterranean; studies have shown that these differences are greater for species introduced by Lessepsian and for aquaculture species. The spatial pattern of biodiversity of native and exotic species is different: The overall richness of native species decreases from northwestern to southeastern regions, while the opposite trend is observed for exotic species [19].

The impact of the exotic migration was enormous on the ecosystem of the Levant Basin, within which the Syrian marine waters lie. The fact that many species have proven successful in the new environment indicates that the nutritional requirements of many migratory species reflect the non-selective nature of their feeding habits. This adaptation is of great importance to any immigrant in its new environment. It is self-evident that successful colonization can only be established when the overlap between the environmental conditions in the source and target regions is within the colonizer's tolerance (**Figure 4**). Since these environments are not identical, the colonizing population will respond to new selective pressures by moving away from the parent population, thus becoming more adapted to their new habitat. The successful establishment of the large number of exotic species raises the question of complex interactions with native species. However, this high number is determined mainly by the ability of the migrants to occupy a niche in the new ecosystem, maintain itself by successful breeding when environmental and hydrological conditions are suitable for reproduction and growth of larvae to maturity, and then replenish and develop their stocks in the new environment.

3.3 Impact of alien species on marine ecosystems

The impact of alien species, known as biological contamination, is something that must be considered in environmental impact assessments [81]. Human-mediated introduction of marine species to a region outside their natural range of distribution is widely considered to be the major threat to indigenous species diversity and community structures. This can cause habitat modifications, changes in ecosystem functioning, introduction of new diseases and parasites, and genetic modifications, such as

Family	Species	Origin	Status	First record	Ref.
Apogonidae	<i>Apogon atradorsatus</i>	South-east pacific	sin	Alshawy et al., 2019a	[21]
	<i>Apogonichthyoides pharaonic</i> (mis id <i>Apogon taeniatus</i>)	Red sea Indo-Pacific	est	Sbaihi and Saad, 1992	[22]
	<i>Cheilodipterus novemstriatus</i>	Indian	est	Ali et al., 2018	[23]
	<i>Epigonus constanciae</i>	Western Mediterranean	N	Sbaihi, 1994 (as <i>Epigonus telescopus</i> (synonyme))	[13]
	<i>Jaydia smithi</i>	Red sea	sin	Alshawy et al., 2017	[24]
	<i>Jaydia queketti</i>	Western Indian Ocean	sin	Al shawy et al., 2019b	[25]
	<i>Ostorhinchus fasciatus</i>	Indo-West Pacific	sin	Al Shawy et al., 2019c	[26]
Argentidae	<i>Aregentina sphyraena</i>	Western Mediterranean		Saad and Sbaihi, 1995	[27]
	<i>Glassanodon leioglossus</i>	Western Mediterranean		Saad and Sbaihi, 1995	[27]
Atherinidae	<i>Atherinomorus forskalii</i> (= <i>Atherinomorus lacunosus</i>)	Red sea Indo-Pacific	est	Saad et al., 2002	[28]
	<i>Atherinomorus lacunosus</i>	Indo-Pacific	sin	Othman et al., 2022	[29]
	<i>Atherinomorus pinguis</i> (= <i>Pranesus pinguis</i>)	Red sea		Saad et al., 2002	[28]
Belonidae	<i>Ablennes hians</i>	Worldwide distribution	sin	Al Shawy et al., 2019d	[30]
	<i>Tylosurus crocodilus</i> (= <i>Tylosrus corma</i>)	Red sea Indian	est	Saad et al., 2002	[28]
Bleniidae	<i>Petrosirtes ancyloodon</i>	Red sea Indian	est	Saad, 2002	[31]
Bramidae	<i>Brama brama</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
Bregmacerotidae	<i>Bregmaceros nectabanus</i>	Atlantic and Indian Ocean and tropical western Pacific	sin	Othman & Galiya, 2019	[32]
Callionymidae	<i>Callionymus filamentosus</i>	Red sea Indo-Pacific	est	Saad and Sbaihi, 1992	[33]
Caproidae	<i>Capros aper</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
Carangidae	<i>Alepis djedaba</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
Carangidae	<i>Naucrates ductor</i>	Eastern Atlantic and Indian Ocean	est	Ali-Basha et al., 2021	[34]
Chaetodontidae	<i>Chaetodon larvatus</i>	Indian	sin	Ali et al., 2017a	[35]
	<i>Heniochus intermedius</i>	Indo-West Pacific Ocean	sin	Saad et al., 2022a	[36]
Champsodontidae	<i>Champsodon nudivittis</i>	Indo-Pacific	est	Ali et al., 2017b	[37]

Family	Species	Origin	Status	First record	Ref.
<i>Clupeidae</i>	<i>Dussumieria elopsoidea</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
	<i>Etrumeus sadina</i> (= <i>Eutrimeus teres</i>)	Red sea Indian	est	Saad, 2002	[31]
	<i>Herklotsichthys punctatus</i>	Red sea Indo-Pacific	est	Saad, 2005	[15]
<i>Cynoglossidae</i>	<i>Cynoglossus sinusarabici</i>	Red sea Indo-Pacific	est	Saad and Sbaihi, 1992	[33]
<i>Dussumieriidae</i>	<i>Dussumieria elopsoidea</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
	<i>Etrumeus sadina</i> (= <i>Eutrimeus teres</i>)	Red sea Indo-Pacific	est	Saad, 2002	[31]
<i>Epigonidae</i>	<i>Epigonus denticulatus</i>	Western Mediterranean		Ibrahim et al., 2023	[38]
<i>Exocoetidae</i>	<i>Parexocoetus mento</i>	Red sea Indo-Pacific	est	Saad et al., 2002	[28]
<i>Fistulariidae</i>	<i>Fistularia commersonii</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
	<i>Fistularia petimba</i>	Atlantic and Indo- Pacific	sin	Hussein et al., 2019	[39]
<i>Gadidae</i>	<i>Micromesistius poutassou</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
	<i>Phycis phycis</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
	<i>Gadiculus argenteus</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
<i>Gobiidae</i>	<i>Oxyurichthys petersi</i>	Red sea	est	Saad and Sbaihi, 1992	[33]
	<i>Silhouetta aegyptia</i>	Red sea Indian	est	Sbaihi and Saad, 1995	[27]
<i>Gobiesocidae</i>	<i>Lepadogaster lepadogaster</i>	Western Mediterranean	N	Saad and Sbaihi, 1995	[27]
	<i>Lepadogaster candolli</i>	Western Mediterranean		Saad and Sbaihi, 1995	[27]
<i>Haemulidae</i>	<i>Pomadasystridens</i>	Indian	est	Saad, 2005	[15]
<i>Hemiramphidae</i>	<i>Hemiramphus far</i>	Red sea Indo-Pacific	est	Gruvel, 1931	[6]
	<i>Hyporhamphus affinis</i>	Red sea Indo-Pacific	est	Saad, 1996	[39]
<i>Heterenchelyidae</i>	<i>Panturichthys flowleri</i>	Western Mediterranean		Sbaihi, 1994	[13]
<i>Holocentridae</i>	<i>Sargocentrum rubrum</i>	Red sea Indo-Pacific	est	Anon, 1976	[12]
<i>Labridae</i>	<i>Pteragogus trispilus</i>	Indian	est	Soliman et al., 2014	[40]
	<i>Symphodus bailloni</i>	Eastern Atlantic	sin	Khrema et al., 2022	[41]

Family	Species	Origin	Status	First record	Ref.
<i>Leiognathidae</i>	<i>Equulites klunzingeri</i> (= <i>Leiognathus klunzingeri</i>)	Red sea Indo Pacific	est	Sbaihi and Saad, 1995	[27]
	<i>Equulites popei</i>	Indo-West Pacific	sin	Ibrahim et al., 2020	[42]
	<i>Leiognathus berbis</i>	Indo-Pacific	est	Alshawy et al., 2016	[43]
<i>Lophotidae</i>	<i>Lophotus lacepede</i>	Western Mediterranean		Ali et al., 2021	[44]
<i>Lutjanidae</i>	<i>Lutjanus fulviflamma</i>	Indo-Pacific:	sin	Saad et al., 2022	[45]
<i>Monacanthidae</i>	<i>Stephanolepis diaspros</i>	Red sea Indian	est	Gruvel, 1929	[6]
<i>Mugilidae</i>	<i>Liza carenata</i>	Red sea Indian	est	Saad, 1995	[46]
<i>Mullidae</i>	<i>Parupeneus forsskali</i>	Indian	est	Ali et al., 2016b	[47]
	<i>Parupeneus rubescens</i>	Indo-West Pacific		Sabour and Masri, 2022	[48]
	<i>Upeneus moluccensis</i>	Red sea Indo-Pacific	est	Gruvel, 1931	[6]
	<i>Upeneus pori</i>	Red sea	est	Sbaihi and Saad, 1995	[27]
<i>Nemipteridae</i>	<i>Nemipterus randalli</i>	Indian	est	Ali et al., 2013	[49]
<i>Ophichthidae</i>	<i>Ophisurus serpens</i>	Atlantic and Indo- Pacific	sin	Al Shawy et al., 2019d	[50]
<i>Ophidiidae</i>	<i>Dalophis imberbis</i>	Eastern Atlantic	rex	Capape et al., 2021	[51]
	<i>Ophidion rochei</i>	Mediterranean and Black Sea	rex	Othman et al., 2020	[52]
	<i>Ophidion rochei</i>	Mediterranean and Black Sea	rex	Othman et al., 2020	[52]
<i>Ostraciidae</i>	<i>Tetrosomus gibbosus</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
<i>Pempheridae</i>	<i>Pempheris rhomboidea</i> <i>Pempheris vanicolensis</i>	Red sea Indo-Pacific	est	Sbaihi and Saad, 1992 as <i>P. vanicolensis</i>	[22]
<i>Platycephalidae</i>	<i>Platycephalus indicus</i>	Red sea Indo-Pacific	est	Saad et al., 2002	[28]
<i>Plotosidae</i>	<i>Plotosus lineatus</i>	Indo-Pacific	est	Ali et al., 2015	[53]
<i>Pomacanthidae</i>	<i>Pomacanthus imperator</i>	Indo-Pacific	sin	Saad et al., 2018	[54]
	<i>Pomacanthus maculosus</i>	Red sea Western Indian Ocean		Capapé et al., 2023	[55]
<i>Pomacentridae</i>	<i>Abudefduf vaigiensis</i>	Indo-Pacific	sin	Saad et al., 2020a	[56]
<i>Priacanthidae</i>	<i>Priacanthus hamrur</i>	Indo-Pacific		Capape et al., 2022	[57]
	<i>Priacanthus sagittarius</i>	Indo-West Pacific	sin	Al Shawy et al., 2019e	[58]
<i>Scaridae</i>	<i>Scarus ghobban</i>	Indo-Pacific	est	Saad et al., 2018	[59]
<i>Scombridae</i>	<i>Scomberomorus commerson</i>	Red sea Indo-Pacific	est	Anon, 1976	[12]
	<i>Scomber indicus</i>	Indo-Pacific	sin	Othman et al., 2023	[60]

Family	Species	Origin	Status	First record	Ref.
<i>Scorpaenidae</i>	<i>Pterois miles</i>	Indian	est	Ali et al., 2016	[61]
	<i>Pterois volitans</i>	Indo-Pacific		Fandi et al., 2022	[62]
<i>Serranidae</i>	<i>Epinephelus areolatus</i>	Indo-Pacific	2 records	Al Mabruk et al., 2021	[63]
	<i>Epinephelus caninus</i>	Eastern Atlantic	est	Saad et al., 2020b	[64]
	<i>Epinephelus fasciatus</i>	Red sea	sin	Foulquie & Dupuy de la Grandrive, 2003	[65]
<i>Siganidae</i>	<i>Siganus javus</i>	Indo-Pacific	sin	Ibrahim et al., 2010	[66]
	<i>Siganus luridus</i>	Red sea Indian	est	Gruvel, 1931	[6]
	<i>Siganus revulatus</i>	Red sea	est	Gruvel, 1931	[6]
<i>Soleidae</i>	<i>Pegusa lascaris</i> (= <i>Solea lascaris</i>)	Western Mediterranean	N	Sbaihi, 1994	[13]
<i>Sparidae</i>	<i>Acanthopagrus bifasciatus</i>	Western Indian Ocean	sin	Saad et al., 2022b	[67]
	<i>Crenidens crenidens</i>	Red sea Indo-Pacific	est	Saad et al., 2002	[28]
	<i>Pagellus bellottii</i>	western Mediterranean	N	Sbaihi and Saad, 1992	[68]
	<i>Pagellus bogaraveo</i>	Eastern Atlantic and west Mediterranean	sin	Saad et al., 2020	[69]
	<i>Pagrus major</i>	Northwest Pacific	sin	Saad et al., 2022	[70]
	<i>Rhabdosargus haffara</i>	Red Sea	est	Saad, 2005	[15]
	<i>Rhabdosargus sarba</i>	Indo-West Pacific	sin	Hamwi and Ali-Basha, 2021	[71]
<i>Sphyraenidae</i>	<i>Sphyraena chrysotaenia</i>	Red sea Indo-Pacific	est	Saad, 2002	[31]
	<i>Sphyraena flavicauda</i>	Red sea Indo-Pacific	est	Saad et al., 2002	[28]
<i>Synanceiidae</i>	<i>Synanceia verrucosa</i>	Indo-Pacific	sin	Ibrahim et al., 2019	[72]
<i>Syndontidae</i>	<i>Saurida lessepsianus</i>	Red sea	est	Anon, 1976 as S.	[12]
	<i>Saurida undosquamis</i>	Indo-Pacific		undosquamis	
<i>Tetraodontidae</i>	<i>Lagocephalus guentheri</i> (= <i>Lagocephalus spadiceus</i>)	Red sea	est	Anon, 1976 as L. spadiceus	[12]
	<i>Lagocephalus lagocephalus</i>	Circumglobal		Alshawy et al., 2019c	[73]
	<i>Lagocephalus scleratus</i>	Indo-Pacific	est	Khalaf et al., 2014	[74]
	<i>Lagocephalus suezensis</i>	Red sea	est	Saad et al., 2002	[28]
	<i>Torquigener flavimaculosus</i>	Indian	est	Sabour et al., 2014	[75]
<i>Theraponidae</i>	<i>Pelates quadrilineatus</i>	Red sea Indo-Pacific	est	Saad, 2005	[15]
	<i>Therapon puta</i>	Red sea Indo-Pacific	est	Saad, 2005	[15]

Family	Species	Origin	Status	First record	Ref.
Elasmobranchii:					
Dasyatidae	<i>Himantura uarnak</i>	Indo-Pacific	est	Ali et al., 2010	[76]
	<i>Himantura leoparda</i>	Indo-West Pacific	sin	Saad et al., 2021a	[77]
Rajidae	<i>Leucoraja circularis</i>	Eastern Atlantic	sin	Alkusaairy and Saad, 2018	[78]
	<i>Leucoraja fullonica</i>	Eastern Atlantic	sin	Saad and Alkusaairy, 2019	[79]
Torpedinidae	<i>Torpedo sinuspersici</i>	Indo-Pacific	cas	Saad et al., 2004	[14]
Jawless fishes (Class: Hyperoartia)					
Petromyzonidae	<i>Petromyzon marinus</i>	Northwestern Atlantic	sin	Saad et al., 2021b	[80]

Table 2. Non endogenous fish in Syrian marine water, category, native range, and first records. Species in alphabetic order within each class and family. (Est = established, sin = single record, case = casual, rex = rang extending).



Figure 4. Red Sea goatfish *Parupeneus forsskali* that was recorded for the first time in the Syrian coast in 2015 [47]; it was able, within only 5 years, to become abundant in the catch with gill nets instead of the rest of the species of the mullidi family, and this is one of the examples of the competition of invasive species with indigenous species.

hybridization with the native taxa [82], rabbitfishes (siganidae) have by now overgrazed a significant part of the eastern Mediterranean coast (including Syrian coast), degrading rich habitats of brown algal forests into bare rock, and such impacts, including completion with native herbivores, are likely to be exacerbated by climate change. In several instances, exotic species will outcompete native species, such as *Fistularia commersonii* and *Pterois miles*, and prey on various fish and invertebrates—some of commercial importance with impacts on both local population and fisheries. Our field study showed that *F. commersonii* is carnivorous and feed on many small fish species, such as *Sardinella* spp., *Sprarus spratus*, *Alosa fallax*, *Boops boops*. About 12–30 individual preys were found in the stomach of every specimen (**Figure 5**). The high fecundity rate, and its rapidly expanding population feeding on fish and some invertebrates, makes a decline of the biomass and causing damage and loss to fisheries yield [83, 84]. On the other hand, the results of a survey study during the years 2013–2014



Figure 5. The content of the digestive tube of one individual of the fish *F. commersonii*, showing 22 individuals of prey belonging to several endemic species of small pelagic fish (and a greater number of these prey were found in other samples in several cases), indicating the danger of this exotic species to native fish fauna, biodiversity, and local fish stocks.

showed that exotic fish (most of them are Lessepsian) constitute more than 27% of the weight catch by artisanal fishing (means gill net and trammel net) and more than 50 of trawl net in Syria [83, 84]. Comprehensive evaluation of the overall consequences of alien introductions must integrate the impact of climate change, which clearly reduces the suitability of the eastern Mediterranean waters (including Syrian waters) to several native fish species. This is already observed in this area, where no indigenous species of tropical origin are replacing the ecological functions of temperate native biota that are compromised by overfishing.

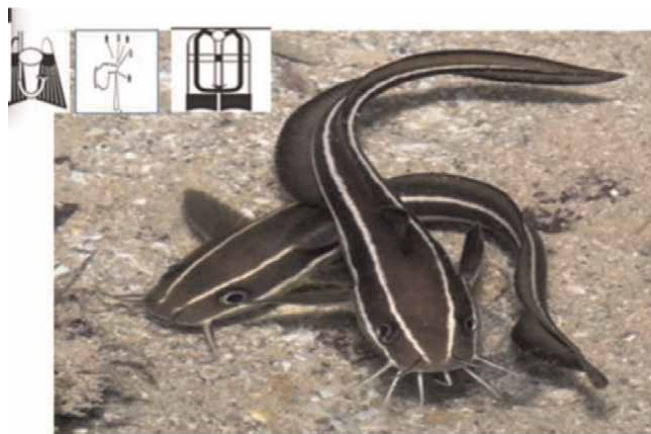
3.4 Impact of non-indigenous species on the public health

Fish invasions in many cases impact human health, and one of the best documented examples is provided the buffer fish *Lagocephalus sceleratus*, which has caused severe damages since its relative recent apparent in Syrian marine waters. The consumption of this invasive species, rich in tetrodotoxin, may lead to severe intoxication, sometimes to death. By examining hospital records in both Lattakia and Tartous during the past 10 years, it is clear that this fish has caused many cases of poisoning and several cases of death for consumers in Syria [85–87].

The marketing of this species is currently banned in Syria and in other Mediterranean countries. To inform local populations about the risks associated with this invasion, Syrian authorities and many non-governmental associations (NGO) have launched awareness campaigns (**Figures 6–8**), which have succeeded in reducing the risk of inadvertent consumption by obtaining information on the occurrence and abundance of this “unwanted guest.” Other dangerous species include *Pterois miles*, *Plotosus lineatus*, *Synnanceia verrucosa*, and two rabbitfishes (*Siganus luridus* and *Siganus rivulatus*) all possessing venomous spines and capable of causing severe injuries [88]. The impact of invasive fishes is not all negative, however. Often food provision is a clear benefit of invasions. That is the case of rabbitfishes, goatfishes (*Upeneus moluccensis*, *Upeneus pori*, *Parupeneus forskali*), and other edible species such



Figure 6. Example of campaign signaling the toxicity of the silver-cheeked toadfish (*Lagocephalus scleratus*) in Syria (by Syrian society for aquatic environment protection (NGO) and general commission of fisheries and aquatic resources). The text illustrates how to distinguish from native pufferfishes. The poster illustrates the risk associated with the consumption of this toxic species.



Striped eel catfish
Plotosus lineatus (Thunberg, 1787)

Figure 7. Example of campaign signaling the poisoning through pricking of striped eel catfish (*Plotosus lineatus*, (by Syrian society for aquatic environment protection (NGO)).

as *Nemipterus randelli*, *Saurida lessepsianus*, and *Scomberomorus commerson*, which have over years developed abundant populations in the Levantine basin, to the point of becoming a target for local fisheries [10, 83].

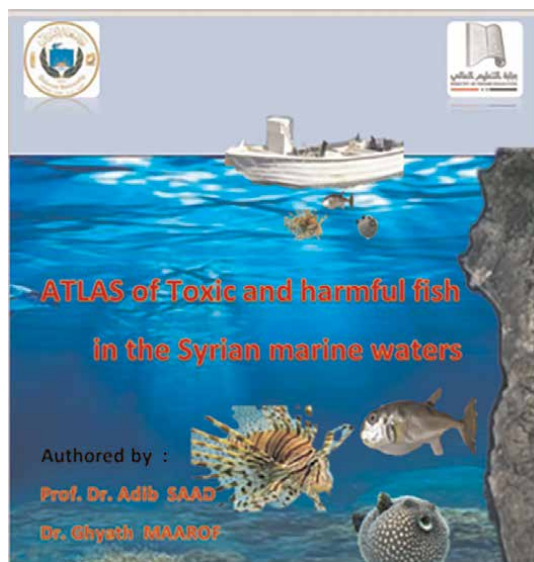


Figure 8. The cover of the Atlas of toxic and harmful fish that threaten human health and community safety, which was published by Tishreen university and the Syrian Society for the Protection of the aquatic environment, addressed to the local population in Arabic [88].

A scientific explanation was provided for each hazard or damage, including toxins contained in certain species. The research also included illustrations of each fish species, explaining the harmful parts of the body, explaining the level of damage and danger caused by each fish species, as well as an explanation of how to prevent damage and the means of treating each type of damage: /9/ poisonous species in their flesh (i.e., poisoning of humans by eating their meat), /3/ poisonous species of blood), and /13/ harmful and poisonous fish species through prickling or stinging poisonous thorns, and/ 4/ types of harmful cartilaginous fish through poisonous stinging with thorns on their body, especially the tail. In addition, / 4 / species of electric fishes that live in Syrian waters were documented (**Figure 8**) [88].

4. Conclusion

The present work elucidates that the marine waters of Syria, as a part of the Levantine basin, are under heavy invasion by alien species, mostly coming from the Red Sea and Indo-Pacific areas. Scientific and public interest in the species introductions and their impacts have resulted in the productions of new papers and synthesis on them and made great contributions to our understanding of the dimensions of this phenomenon. Therefore, this up-to-date inventory of the alien species on the coasts of Syria, apart from its scientific merits, can fulfill the needs of the regulatory requirements and environmental management options for decision makers. Unfortunately, strict precautions and regulations to limit the spread of invasive species have not been implemented in Syria.

It is necessary to consider the classification of non-indigenous and modern species, because these species, which differ in terms of entry pathways, also differ from each

other in the ecological, social, and economic effects that they cause in the new environment (predatory fish and competition in the ecological habitat), as well as their impact on the community health of the population, locals, fishermen, and consumers (poisonous and stinging fish). These differences have been demonstrated by ecological and biological studies and practical solutions in the literature. In addition, these differences will directly affect the precautions taken in the sustainable management of the ecosystem and will therefore affect the success of these precautions.

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Conflict of interest

The authors declare no conflict of interest.

Author details


Adib Saad^{1*} and Lana Khrema²

1 Directorate of Scientific Research, Manara University, Lattakia, Syria

2 Faculty of Agriculture, Tishreen University, Lattakia, Syria

*Address all correspondence to: adibsaad52@gmail.com; manara.edu.sy

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Chapter 6

Fish Otolith Microchemistry as a Biomarker of Metal Pollution in the Estuarine Ecosystem

Abhijit Mallik, Suchismita Prusty, Puja Chakraborty, Shyamal Chandra Sukla Das and Shashi Bhushan

Abstract

Numerous metal pollutants naturally find their way into estuaries, where many of them build up in the bodies of fish. While otoliths can give a historical record of pollution exposure, metal concentrations in soft tissue and water samples require ongoing, long-term sampling procedures. Fish have otoliths, which are three pairs of ear bones called the sagitta, lapillus, and asteriscus. The chemical makeup of these otoliths can be a useful tool to determine the presence of hazardous substances in fish because the physiological activity of fish is controlled by a variety of environmental factors. The possible use of otoliths as inorganic tracers of metal contamination will be covered in this chapter.

Keywords: otolith, estuaries, pollution, biomarker, fish

1. Introduction

In aquatic environments, heavy metals stand out as the primary pollutants due to their widespread distribution and substantial presence. They tend to amass within the tissues of freshwater organisms, leading to fish poisoning and causing diverse effects across multiple biological levels, often resulting in pathological alterations. The majority of fish have otoliths, or “ear-stones,” which are calcium carbonate structures that aid in hearing and balance and are located below the brain. The otoliths float in fluid-filled sacs in the inner ear and are not connected to the skull or any other bone. The three pairs of otoliths most common to fish are the sagitta (the largest pair), lapillus, and asteriscus [1]. Only fish with cartilage (such as sharks, rays, and chimeras) and fish without jaws (such as lampreys and hagfish) lack otoliths. Black drum (*Pogonias cromis*) and Atlantic croaker (*Micropogonias undulatus*), two fish that inhabit artificial habitats and vocalize during mating, have exceptionally large otoliths. The relatively smaller otoliths of species that swim continually, including bluefin tuna (*Thunnus thynnus*) and alewives (*Alosa pseudoharengus*), may be an attempt to control excessive movement. The most popular applications for sagittal otoliths, which are hard, porous calcium carbonate structures in teleost fish inner ears, are population and microchemistry investigations. They play a role in

fish hearing, motion, displacement, sensation, and linear acceleration [2]. Calcium carbonate crystallites implanted in a protein lattice mineralize to produce otoliths, which then continue to grow [2]. Metals are among the major chemical toxicants polluting the environment due to their prolonged persistence and complex interactions with organisms in aquatic ecosystems. Consequently, changes in metal levels can be reflected in aquatic organisms, serving as biological indicators of metal exposure [3]. The concentration of metals in fish tissues mirrors their exposure through water and/or food and serves as a means to evaluate the present condition of these organisms before the onset of adverse toxic effects. Nevertheless, excretion mechanisms modify the accumulated metal burden over time. As assessments of accumulation levels are typically sporadic, they cannot serve as markers for constructing comprehensive lifetime accumulation histories. However, the toxic impact of metals is notably pronounced during the early phases of fish development, significantly affecting various metabolic processes and leading to developmental delays, morphological and functional abnormalities, or mortality in the most vulnerable individuals. Substantial accumulation levels throughout an entire lifespan or during critical developmental stages can detrimentally impact the future of populations. If necessary, trace elements can be absorbed into either the organic or inorganic component of the developing otolith. The elemental incorporation of metal contaminants in the aragonite matrix of the otolith is not a simple function as the process is species-specific [3], driven by environmental conditions [4], and route of exposure [5]. Studies on the application of otoliths in the metal exposure assessment of aquatic ecosystems and their comparison to soft tissues as bioindicators are rare. Thus, it is very important to assess whether metal accumulation in hard tissues (scales, otoliths) reflects metal exposure in correspondence to soft tissues (liver, muscle) of fishes [5].

2. Metal pollutants in estuaries

Estuarine ecosystems serve as crucial transition zones between ocean and river ecosystems, boasting high productivity in aquatic environments. These areas are home to a diverse array of fish species, many of which hold significant commercial value. Estuaries play essential ecological roles, serving as nursery areas for juvenile fish, feeding grounds for resident and adult fish, and temporary environments for the reproduction and migration of various species [6].

Given their ecological significance, estuaries provide valuable goods and services for human activities. However, these ecosystems face growing anthropogenic pressures, particularly from pollution. Estuaries naturally act as sinks for a variety of metals, accumulating them at concentrations that, while potentially highly toxic, are generally non-lethal. This accumulation of metals poses a threat to the overall health of estuarine ecosystems [7].

Metal pollution poses a worldwide challenge in estuaries, stemming from historical contamination legacies and ongoing increases in metal emissions. Nevertheless, establishing water and sediment standards or implementing effective management strategies in brackish systems has proven challenging, primarily due to the complex, multidisciplinary nature of estuarine processes. As per the European Commission, achieving an integrated understanding of the fate and effects of contaminants across various compartments of these transitional environments (including estuarine sediment, water, and biota) is still necessary to more effectively establish, evaluate, and monitor the targeted good ecological status outlined by the Water Framework

Directive [8]. Numerous environmental issues stemming from human activities like industrialization and urbanization are faced by this ecosystem. Physical, chemical, and biological processes all play significant roles in the metal biogeochemical cycle in this complex coastal environment. However, metal pollution in the coastal area has been brought on by anthropogenic factors, including urbanization and industrialization. Since most metals can poison organisms when present in amounts over threshold levels, this issue is getting more and more serious [9]. The sources include mining, the production of metal products, the disposal of solid waste, the burning of fossil fuels, and municipal and industrial waste effluent [10–12]. Particle size, amounts of particulate and dissolved organic matter, and many other variables all have an impact on the amount of exchangeable metal stored in the sediment. Thus, it indicated decreased cobalt and cadmium adsorption and enhanced zinc adsorption [13]. It is generally known that benthic fauna can serve as a sign of heavy metal contamination [14]. Several aquatic species including *Tittorina* sp., *Patella* sp., *Mytilus edulis*, *Scrobicularia plana*, *Macoma* sp., *Nucella* sp., and *Nereis* sp. are among the species and/or genus that are frequently employed. Heavy metal concentrations in all of these creatures could be thousands of times higher than they are in the water column. Therefore, heavy-metal concentrations can be easily and reliably determined as long as enough material can be gathered. However, seasonal fluctuations in metal content have been identified in several benthic mollusks [15]. The degree of toxicity of various metals in estuarine organisms varies depending on the chemical form of the metal in the solution [16]. The composition of both organic and inorganic ligands in the medium influences the free metal ion, which in turn affects the availability and toxicity of trace metals. As a result of complexation with chloride ions, it has been demonstrated that the concentration of free cadmium ions in solution varies inversely with salinity [17]. Other trace metals may behave similarly, making it likely that the estuarine biota's access to them will frequently rely on the surrounding medium's salinity. Unlike freshwater systems, where nutrients primarily limit primary production, the growth of phytoplankton in coastal zones is predominantly constrained by a complex interplay of factors, including nutrient loading, the system's filtering capacity, contaminants, light availability, and ecological interactions. For example, exposure to less than $90 \mu\text{g}\cdot\text{L}^{-1}$ of Cu or Zn has been shown to result in growth reductions of up to 50% for cosmopolitan phytoplankton species. Laboratory experiments simulating metal exposure have indicated that phytoplankton may experience reduced cytokinesis, disturbances in photosynthesis, and increased cell size in response to various metals and species [8]. In contaminated estuaries, it is evident that cellular concentrations of metals may reach toxic levels, exerting control over growth and potentially leading to alterations in phytoplankton productivity and species composition [18]. Nevertheless, the quantitative significance of these effects under environmental conditions is yet to be fully elucidated.

Ultimately, the physical and chemical gradients within estuaries play a crucial role in shaping biogeochemistry and organism physiology, thereby influencing the exposure and toxicity of organisms. The significance of each gradient in determining the behavior and toxicity of metals can vary considerably and show seasonal variations. For example, the impact of salinity on partitioning coefficients may be significantly influenced by fluctuations in river flow, input of particulate and organic matter, and phytoplankton growth. Consequently, the behavior and effects of metals in estuaries are dynamic and depend on both environmental and biological factors. These dynamics must be taken into account when establishing site-specific water quality criteria and environmental quality targets [19].

3. Trace metal accumulation

To date, a comprehensive analysis has identified 51 elements in otoliths, encompassing major components such as calcium (Ca), carbon (C), oxygen (O), and nitrogen (N), as well as minor elements like sodium (Na), strontium (Sr), phosphorus (P), magnesium (Mg), potassium (K), chloride (Cl), and sulfur (S). Additionally, numerous other elements are present at trace levels. Otolith microchemistry has emerged as a sclerochronological biomarker for aquatic pollution by metals. The majority of these elements exist at micro and trace levels, necessitating thorough investigation for detection [20]. The incorporation of elements into the otolith can occur through one of three mechanisms: random entrapment in the crystal lattice, calcium substitution on the developing crystal surface, and binding to the organic matrix components. This suggests that the otolith's chemical composition reflects certain physicochemical features of the surrounding water. Recently, the otolith microchemistry of trace elements has gained recognition as a valuable technique for providing insights into a fish's life cycle and environmental history, particularly challenging information to obtain otherwise. However, its application has been limited in studies related to freshwater environments [21]. The concept of the bioaccumulation factor provides insight into the absorption of metals by fish from their environment. The variation in accumulation capacity in fish tissues is influenced by a combination of external and internal factors. The metal accumulation in fish tissues is species-specific, meaning that the concentration of certain metals may be higher in one tissue compared to another. Whereas the elemental signatures found in otoliths establish a baseline for quantifying pollution levels in the wetland [22].

The metal build-up has been studied using otolith chemical analysis. Many different trace metals, such as Sr, Mg, Mn, Fe, Cu, Co, Ni, Zn, Rb, Li, and rare earth elements, can be incorporated into the structure of carbonate minerals [23]. For many years, researchers have exploited the uptake of metals into the aragonite lattice of fish otoliths (ear bones) as a historical record of exposure to metals in polluted habitats. In the forensic chemical examination of crude oils, the relative abundance of two metals, in particular Ni and V, is utilized to help establish the origin of the oil. Ion size and crystallization temperature are two significant restrictions on trace metal substitution. The oxidation state of the elements, the alkalinity, and metabolism of the organism, the nutrition, and their quantities in the water could all affect ionic substitution in biogenic carbonates. The inner ears of teleost fish include calcified structures called otoliths. Otoliths are made up of calcium carbonate crystals, typically aragonite, that accumulate over the course of a person's lifetime within a protein matrix. The organic or inorganic part of the otolith can contain trace amounts of several different elements during creation. It is believed that the fish's environment has the biggest impact on the concentrations of these trace elements. According to their concentration in the surrounding water, certain elements, such as Sr, Ba, Hg, and Pb, seem to be deposited in otoliths [24]. Furthermore, changes in environmental contamination through time and space have been linked to the amounts of heavy metals in otoliths [25]. The element strontium, which frequently takes the place of calcium ions in carbonates, has by far received the most attention in relation to this phenomenon. Although a number of environmental and physiological factors influence how much strontium is incorporated into fish otoliths, the amount of strontium in the surrounding water is crucial. Zinc was found in some otoliths [26]; however, the precise distribution of zinc was unknown to them. The lithosphere, particularly

the rocks encircling the water in which the fish lives, must be the primary source of zinc in the ecosystem. Zinc availability and uptake by fish, however, appears to be influenced by both the environment they are in and their physiological processes. Food appears to be the main source of zinc uptake in seawater. A similar analysis does not seem to have been done in freshwater. Additionally, the fish may very likely take up zinc by active ion transport through the gills. The heating regime, pH, alkalinity, and amount of particulate matter in the water are all dependent on the type of aquatic habitats, such as the availability of zinc, food-chain bio-magnification, and zinc flux. Analysis of zinc in addition to strontium may be able to provide temporally restricted information on habitat environment and fish migration if zinc exhibits a systematic distribution in otoliths along the life history transect [5].

4. Otolith microchemistry

Otolith microchemistry stands as a potent tool for investigating life stage dispersal, and regional connectivity, evaluating population structure, delineating estuarine nurseries, gauging connectivity between juvenile and adult populations and, to a lesser extent, serving as an indicator of environmental pollution. The continuous accretion of otoliths, coupled with their metabolic inertness and resistance to resorption, results in the permanent incorporation of various elements from the local environment into the crystalline matrix [27]. While otolith microchemistry can reflect a blend of local environmental chemistry and individual physiology, the resultant elemental composition acts as a distinctive fingerprint, functioning as a natural tag for distinguishing location and inferring ontogenetic changes, enabling the differentiation of otolith microstructures from various environmental conditions or locations. Consequently, marine organisms inhabiting impacted areas are likely to accumulate metals, including anthropogenic ones, from their surroundings and subsequently transfer or transport them into higher trophic levels of the food chain [28].

Otoliths, which are the calcium carbonate (CaCO_3) earstones of fish, offer a rich source of information about the life and environmental history of fish. However, the specific CaCO_3 polymorph forming the otolith represents a critical yet often overlooked aspect during otolith analysis. While otolith trace element chemistry data increasingly plays a crucial role in informing management decisions, recent research indicates that the CaCO_3 polymorphs—aragonite, vaterite, and calcite—can significantly influence the incorporation of trace elements in a non-trivial manner. While it has been traditionally believed that most fishes have otoliths composed of the aragonite CaCO_3 form, recent literature reports challenge this assumption, suggesting a more diverse landscape in otolith composition [29]. Studies on the microchemistry of otoliths in urban settings are particularly important since metal pollutants are more concentrated in urban areas than in natural ecosystems. Copper (Cu), zinc (Zn), and lead (Pb) are common metals found in metropolitan areas. Fish otoliths may include metals that have been deposited there from a variety of environmental compartments. They can be found in food sources, bonded to the sediment, present in sediment porewater, and also in the water column [30]. In order to estimate the possibility of a biological influence in aquatic environments, sediments are frequently evaluated as a line of evidence and known to be a repository of contaminants [31].

5. Conclusion

The fish otolith, commonly known as the earstone, has traditionally served as a timekeeping structure. However, recent years have seen a surge in interest in its use as a metabolically inert environmental recorder, driven in part by technological advancements. Various applications have emerged, including stock identification, determination of migration pathways, reconstruction of temperature and salinity history, age validation, detection of anadromy, utilization as a natural tag, and chemical mass marking. Some of these applications are challenging or even impossible to achieve using alternative techniques. Microsampling and the latest developments in beam-based probes now enable the coupling of elemental assays with daily or annual growth increments in the otolith, offering a detailed chronological record of the environment. Despite these advancements, there has been limited critical assessment of the assumptions underpinning environmental reconstructions or consideration of potential variations in elemental incorporation compared to other calcified structures. Drawing on insights from recent advances in geochemistry and paleoclimate research for comparison, it becomes evident that not all applications of otolith chemistry are firmly grounded, although some are poised to become powerful and perhaps routine tools for mainstream fish biologists.

Over the past three decades, otolith microchemistry has been a valuable tool in various studies, including those focused on the life history, migration patterns, and environmental ecology of commercially important fish stocks. Comparisons are made between the concentrations of elements and isotopes in otoliths and those in the water where the fish resides. The accumulation of heavy metals in fish otoliths is influenced by several factors, including the concentration of the specific heavy metal in the environment, its bioavailability, and the physiological state of the individual fish (which affects the exchange rate between external and internal environments). The chemical composition of otoliths is regulated by the physiological activity of fish, itself influenced by environmental conditions. The concentration of heavy metals in the calcified otoliths of fish serves as a tracer of environmental pollution exposures. Analyzing the microchemistry of fish otoliths provides a potent tool for monitoring pollution levels in aquatic ecosystems. These trace elements have the potential to serve as a biomonitoring tool, distinguishing between metals in different seasons. It is evident that the accumulation of heavy metals in fish otoliths depends on a variety of factors, including the concentration in the environment, bioavailability, the physiological state of the individual fish (affecting the exchange rate between the external and internal environments), the mechanisms of various species for detoxifying various metals, the growth rate of the individual fish (affecting the rate of accumulation of otolith material), and the affinity of certain heavy metals for particular fish species. In instances when metal pollution is low enough not to affect fish growth, it is more likely that the rate of metal accumulation will be higher since otoliths develop more quickly in individuals who grow more quickly. Other divalent cations, including Mg, Sr, Ba, Mn, Cu, Zn, and Pb, as well as smaller monovalent cations like Li can alter the amounts of various elements across the otoliths of individual fish. However, it has also been proposed that bigger cations and anions, including Mg, can be integrated by being trapped within the crystal lattice as crystal inclusions.

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Conflict of interest

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Author details

Abhijit Mallik^{1,2*}, Suchismita Prusty¹, Puja Chakraborty¹,
Shyamal Chandra Sukla Das³ and Shashi Bhushan¹


1 ICAR-Central Institute of Fisheries Education, Mumbai, India

2 Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University,
Jamuhar, Bihar, India

3 ICAR-Central Inland Fisheries Research Institute, Guwahati, India

*Address all correspondence to: abhijitmallik1993@gmail.com

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Marine ecosystems are very productive and include the open ocean, the deep-sea ocean, and coastal marine ecosystems, each of which has different physical and biological characteristics. The biodiversity of some of these ecosystems is very rich and abundant, offering unique opportunities for high-yield production of proteinaceous material, which is a source of high-quality foods. Biodiversity is fundamental to sustaining marine ecosystem services, such as food security, maintenance of water quality, and recovery from perturbations, which are currently being threatened worldwide. The main threats to marine biodiversity are habitat loss, eutrophication, overexploitation, pollution by hazardous substances, introduction of non-native species, and other human activities. Efforts to reduce these pressures are essential for coastal water quality, recovery of ecosystem services, global food security, and ecosystem stability. Bioindicators are important tools to be used as early warning signals to detect the presence of natural and chemical stressors when monitoring and managing ecosystems and thus promoting ecosystem health. The protection of biodiversity is a major target of the European Union Marine Strategy Framework Directive, requiring an assessment of the status of biodiversity on the level of species, habitats, and ecosystems, including genetic diversity and the role of biodiversity in food web structure and functioning. The restoration of marine ecosystems can support the productivity and reliability of goods and services that the ocean provides to humankind to maintain ecosystem integrity and stability. Some of the goods produced by the marine ecosystem services are fish harvests, wild plant and animal resources, water, and services that provide recreation, tourism, breeding and nursery habitats, water transport, carbon sequestration, erosion control, and habitat provision. This book comprises six chapters that discuss the ecological, economic, and social roles of a variety of organisms, from primary producers to consumers, relating these roles with water quality and conservation of estuarine and marine ecosystems and thus the contribution to human health.

J. Kevin Summers, Environmental Sciences Series Editor

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